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Spin Stability of the Explorer Satellite

by

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PART I: INTRODUCTION - SPIN STABILITY OF THE EXPLORER SATELLITE*

According to the classical laws of dynamics of rigid bodies, the conditions for the stability of rotation of a body may be summarized as follows (see reference I-1;

> "If a body is rotating about a principal axis which is one of either maximum moment of inertia or minimum moment of inertia, the state of motion is stable; but if the axis of rotation is the intermediate principal axis, the state of motion is unstable."

The first U. S. satellite, the Explorer was designed in accordance with the above mentioned laws to spin about the axis of minimum moment of inertia at a rate of about 10 revolutions per second. From observations of its antenna pattern it was deduced that after about one orbit the spin rate decreased to about 2 cycles per second and that its spin axis had rotated about 90°, so that it was now spinning about its axis of maximum moment of inertia. The weights and dimensions of Explorer were as shown in Figure I-1. The launching system consisted of the four stage rocket assembly shown in Figure I-2. The first stage was a high performance version of the REDSTONE ballistic missile. Stage II consisted of a cluster of 11 solid propellant rockets. Within this cluster was nested stage III consisting of three solid propellant rockets. On top of stage III was mounted in tandem the fourth stage, a single solid propellant rocket which also carried the payload. The entire assembly of solid propellant rockets was mounted in a tub on top of the REDSTONE missile. This entire tub was rotated in order to average the thrust dispersion effects of the individual motors and to provide gyroscopic stability.

The Explorer telemetered its scientific observations perfectly; however, there was a question as to what had caused this dynamic

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Reference I-1: E. Howard Smart-Advanced Dynamics, Volume II-Dynamics of Rigid Bodies - page 211

*This section is based largely upon the following report:

Reference I-2: William C. Pilkington, Vehicle Motions as Inferred from Radio-Signal-Strength Records - External Publication No. 551 of the Jet Propulsion Laboratory, California Institute of Technology - Sept. 5, 1958.

anomoly of the change in spin axis. Were the observations in error? Figure I-3 shows the variation in signal intensity. Because the antenna pattern of the satellite transmitters was not perfectly symmetrical about the axis of rotation of the body, the spin rate was fairly easily read from the records. In addition to this high frequency variation in signal strength it was found that there was a low frequency signal strength variation which might be either due to ionospheric variations or due to a precession of the vehicle. If it is assumed that this effect is due to precession of the vehicle then the half-angle of precession θ can be determined by observing the distance between antenna nulls (see Figure I-4). The antenna on Explorer I consisted of four flexible whips attached to the body of the satellite (see Figure I-5).

Explorer II was launched on March 5, 1958 but did not attain orbit because the fourth stage did not ignite. Explorers III and IV were launched successfully on March 26, 1958 and July 26, 1958 respectively. On these two satellites the flexible whip antenna was removed and replaced by an integral antenna built into the body of the satellite. The dynamic behavior of these two satellites was, however, again similar to that of Explorer I, except that the reduction in spin rate occurred over a period of 10 days (see Figure I-6). Figure I-7 shows the low frequency variation of signal strength variation due to a tumbling or precessional motion.

Problem I-1: Try to analyze the various possibilities for this anomolous dynamic behavior. Some of the questions which were raised included the following:

(1) Were the observations of the high frequency roll rate in error?

(2) Was the interpretation of the low frequency pitch precession in error?

(3) Were the laws of dynamics incorrect, or were they improperly interpreted?

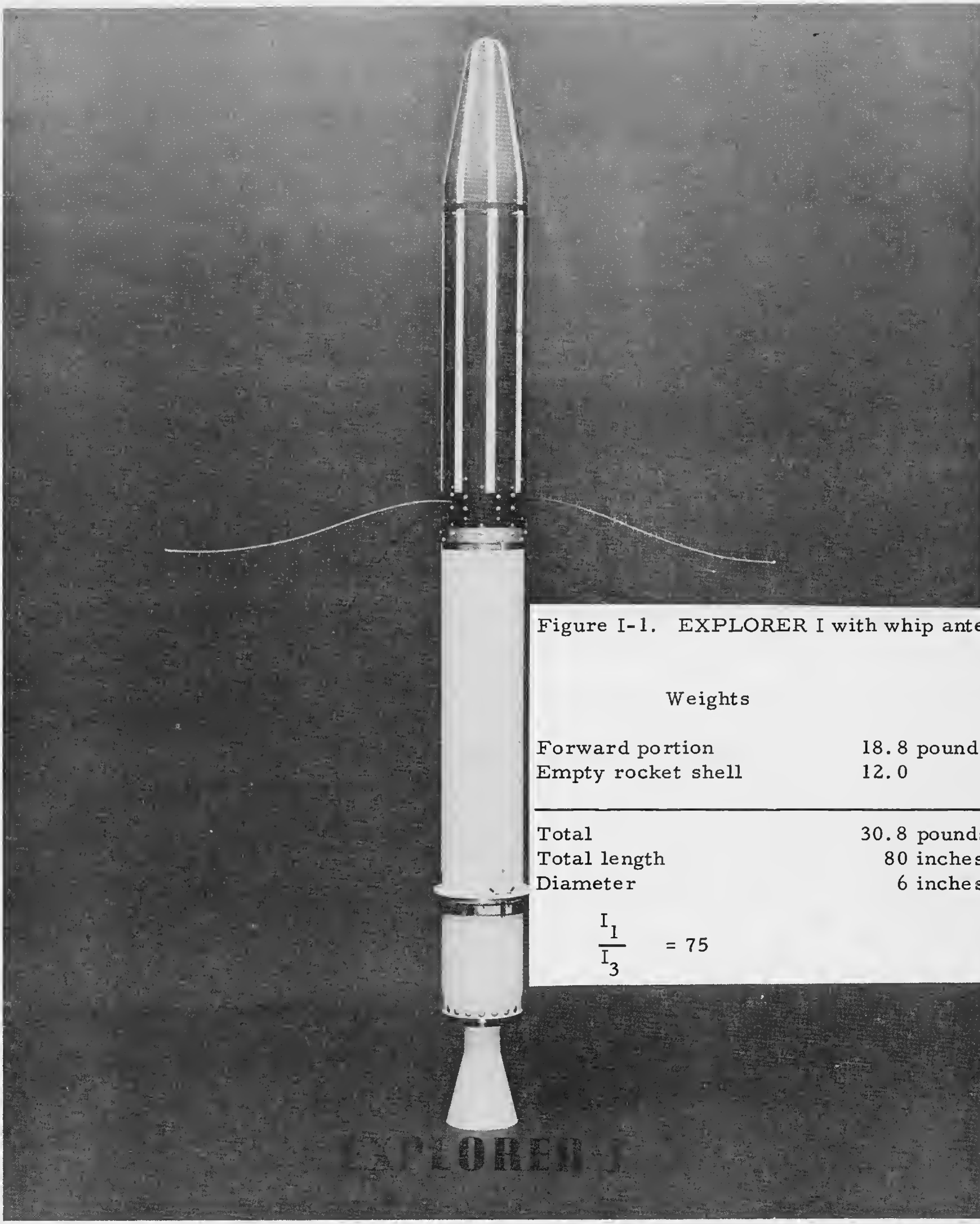

Figure I-1. EXPLORER I with whip antenna

Weights

Forward portion	18.8 pounds
Empty rocket shell	12.0
Total	30.8 pounds
Total length	80 inches
Diameter	6 inches

$$\frac{I_1}{I_3} = 75$$

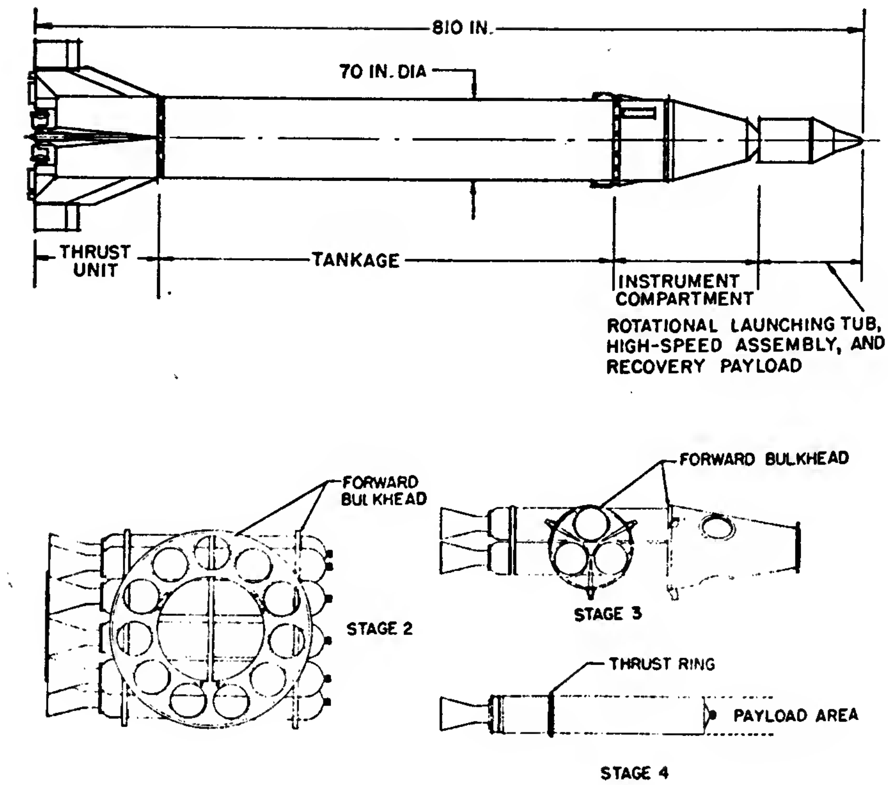

Figure I-2. The Launch Rocket System for Explorer I

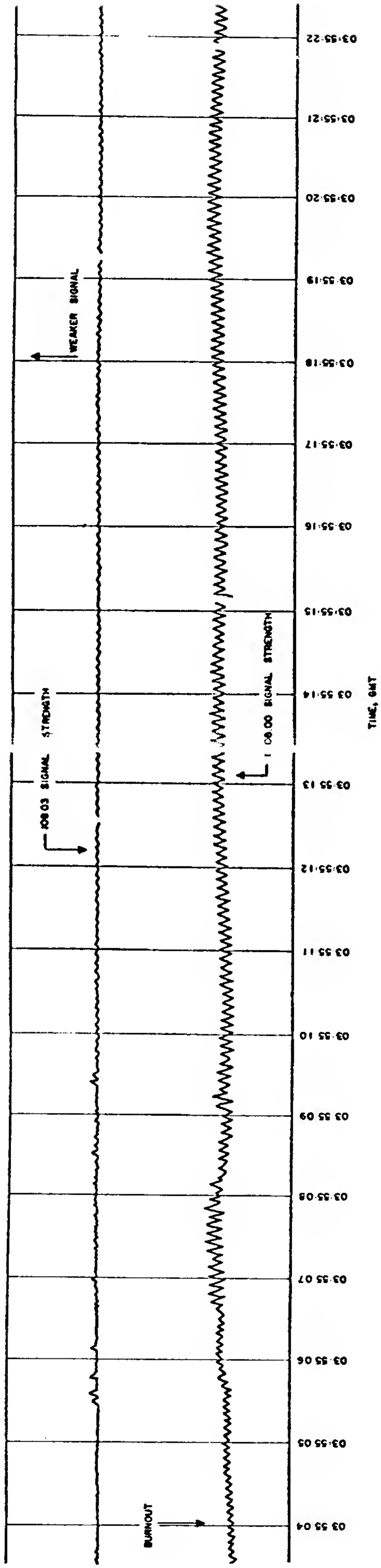

Figure I-3. Reproduction of a Portion of the Signal-Strength Record of Explorer I

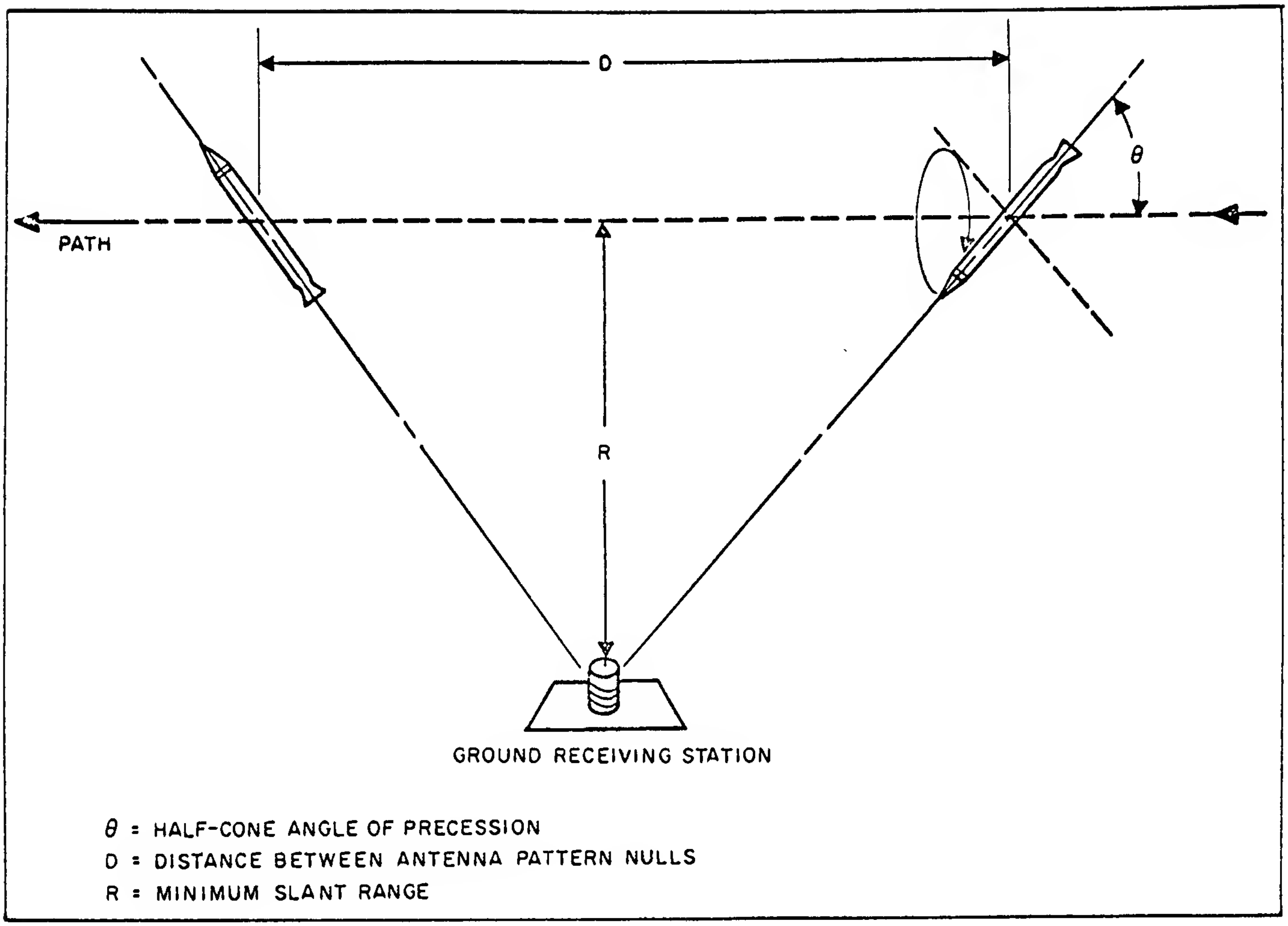

Figure I-4. Method of Obtaining Cone Angle of Precession by Direct Evaluation of Signal-Strength Records

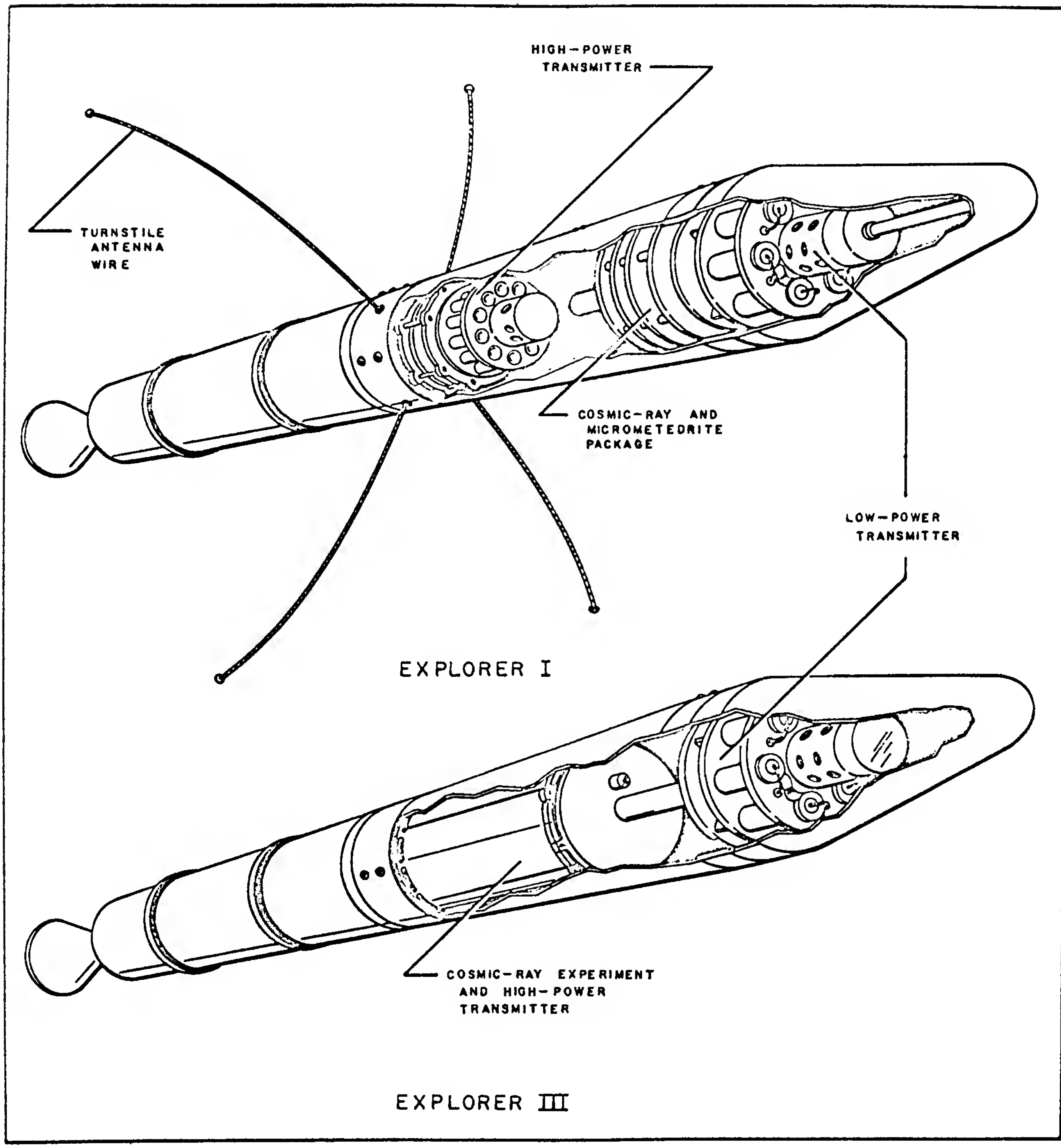

Figure I-5. Cutaway View of Explorers I and III

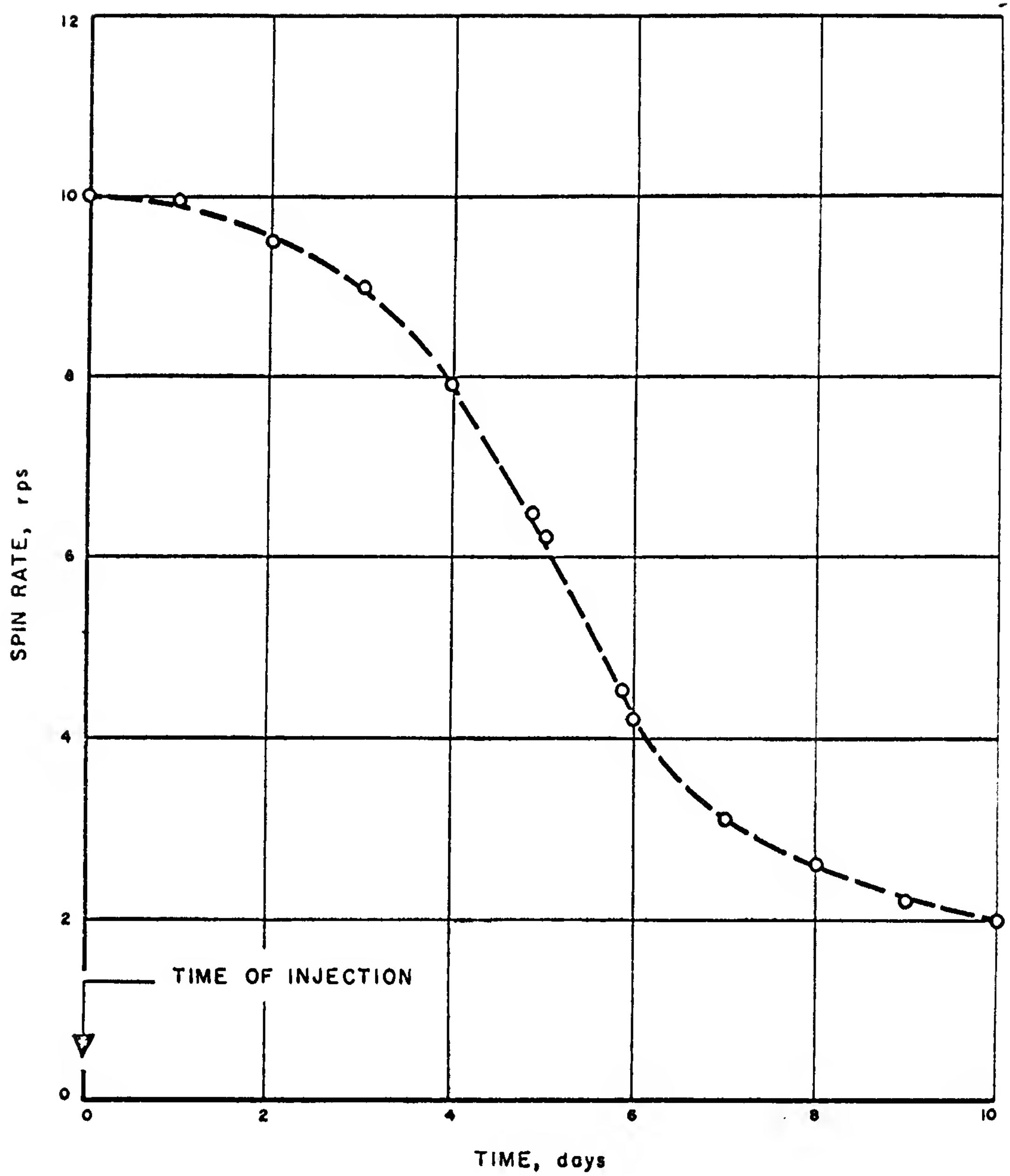

Figure I-6. Plot of Spin Rate vs. Time for Explorer III after Injection

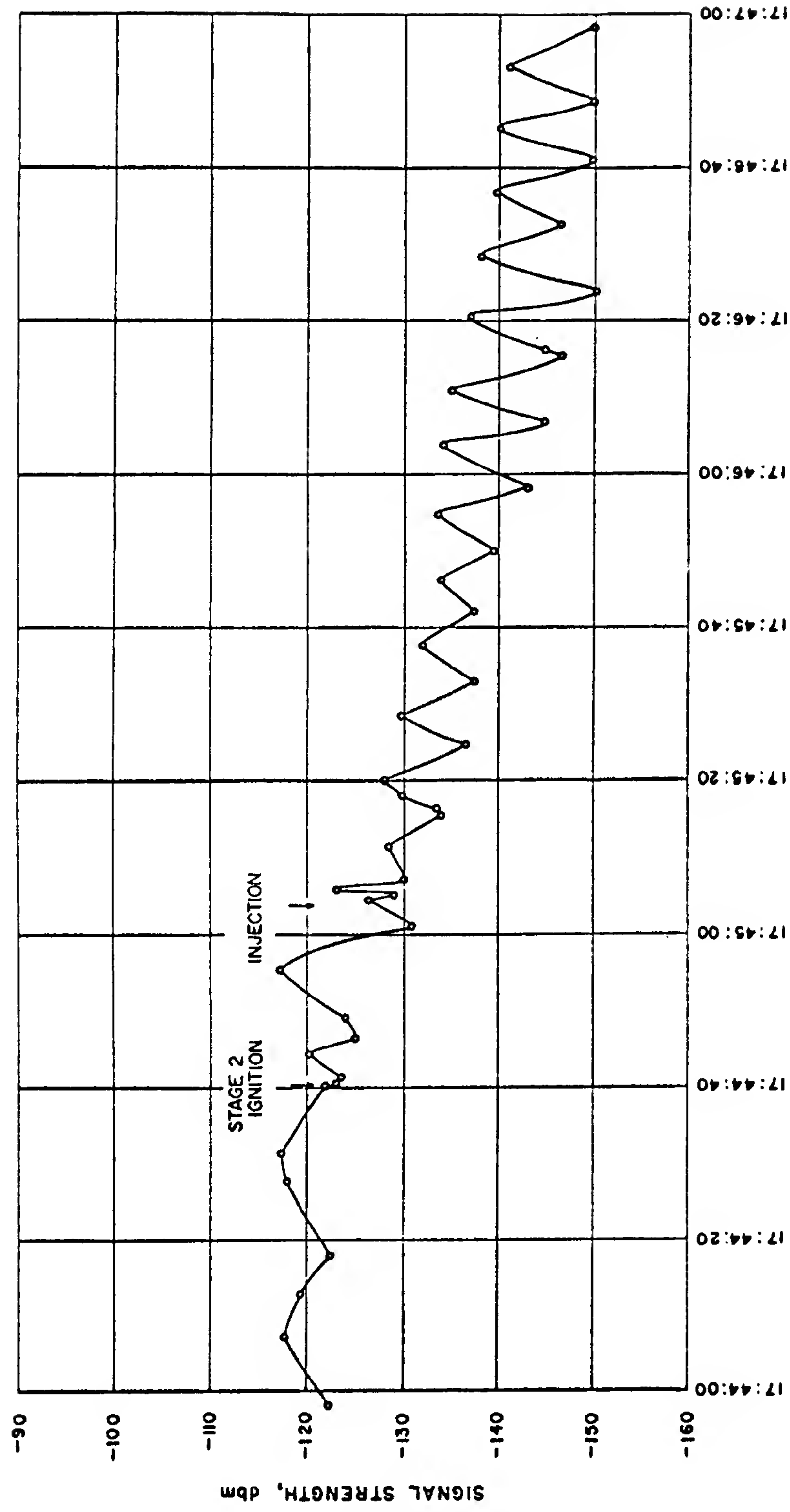

Figure I-7. Plot of Signal Strength vs Time for Explorer III Launch

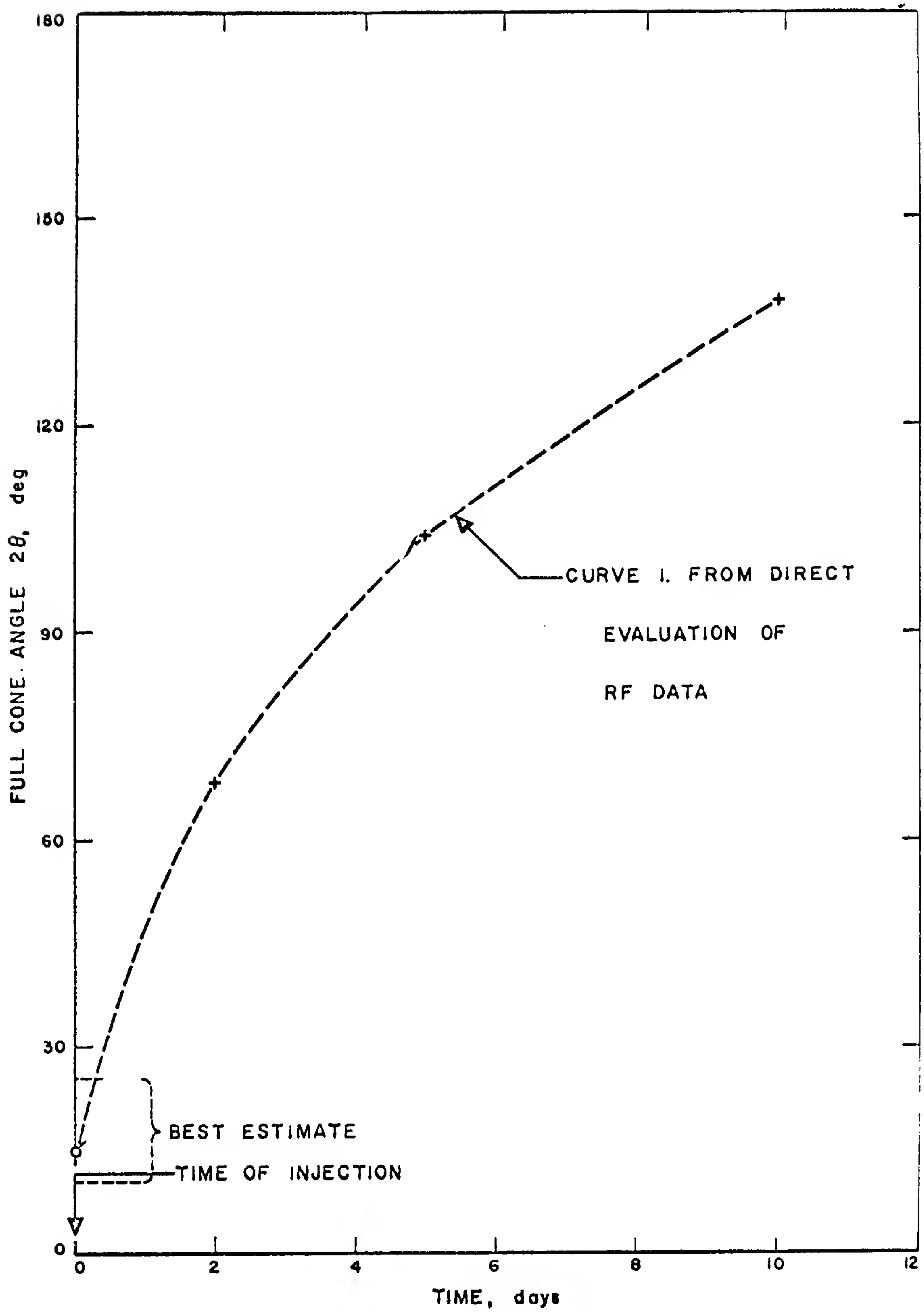

Figure I-8. Plot of Approximate Cone Angle of Precession vs. Time for Explorer III

PART II: ANALYSIS OF THE DYNAMICS OF THE EXPLORER SATELLITE

The following analysis of the tumbling of the Explorer Satellite was prepared by Mr. Willard Wells, and is contained in the appendix of reference 1, under the following heading:

Spin Stability of Space Vehicles and the Tumbling of Explorer I
by
Willard Wells
Research Engineer, Jet Propulsion Laboratory

Introduction

The rotation of a rigid body is stable if the body is rotating about the axis of least or greatest moment of inertia. If the body is nearly rigid, but has some part which moves slightly with friction, then only rotation about the axis of maximum moment is stable

The purpose here is to study nearly rigid bodies and their rate of transition from rotation about any axis to stable rotation about the axis of maximum moment. Knowledge of this transition time is important in designing space vehicles which are required to have a stable attitude. In the case of a saucer-shaped vehicle, the transition time is the time required for the attitude to become fixed after some perturbation. In the case of cigar-shaped vehicles, such as the Explorers, the initial spin[4] about the symmetry axis is an unstable equilibrium. The transition time tells how quickly an operation requiring fixed attitude must be performed before tumbling sets in.

The general problem will be reduced to the following form. A formula will be derived for the forces which act on the frictional parts in terms of the parameters which describe the location of the frictional parts in the vehicle and the rotation of the vehicle as though it were

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Ref. 1: William C. Pilkington - Vehicle Motions as Inferred from Radio-Signal Strength Records including Appendix by Willard Wells "Spin Stability of Space Vehicles and the Tumbling of Explorer I", External Publication No. 551 - Jet Propulsion Laboratory, 5 Sept. 1958.

[4] The word spin will always refer to angular velocity about the symmetry axis; tumbling, to angular velocity at right angles to this axis.

rigid. From these forces the rate of energy dissipation must be found either theoretically or by reproducing the forces in the laboratory. The energy dissipation rate than goes into another formula (Eq. C-10) to give the slow rate of change of parameters which would be constant for a perfectly rigid body.

Explorer I was a nearly rigid body rotating initially about its unstable axis of least moment. The most important frictional parts were the whip antennas. The change of Explorer I from unstable spin motion to the stable tumbling motion is analyzed as an example of the above method. The results agree well with radio data.

Rigid Body Motion

The motion of free rigid bodies is derived in many mechanics texts (Refs. 2, 3). The results of the derivation will be summarized here. Let I_1, I_2, and I_3, be the principal moments of inertia of the rigid body. In the case of a symmetrical body, I_3 is the moment about the symmetry axis and $I_1 = I_2$. The body will be represented by its so-called ellipsoid of inertia (Ref. 2) which is long or short in the same general directions as the mass distribution of the body it represents. Thus, the ellipsoid for Explorer I is cigar-shaped. The equation of the ellipsoid is

$$1 = I_1 \rho_1^2 + I_2 \rho_2^2 + I_3 \rho_3^2$$

where ρ_1, ρ_2, and ρ_3 are coordinates along the principal axes. The ellipsoid intercepts the principal axes at distances $I_1^{-1/2}$, $I_2^{-1/2}$, and $I_3^{-1/2}$. For Explorer I, these are in the ratio of about 1, 1, 8.7. Imagine the body contained in the ellipsoid and rigidly attached so that the center of mass (CM) lies at the center of the ellipsoid, and the principal axes coincide. Then the motion of the ellipsoid gives the motion of the body. The most general motion is as follows: the ellipsoid rolls without slipping on a plane while its center is fixed. The angular momentum vector L is perpendicular to the plane as shown in Fig. C-1. The angular velocity vector $\vec{\omega}$ passes through the CM and the point of contact with the plane, since these points are stationary. While $\vec{L}$ is fixed in space, $\vec{\omega}$, in general, changes direction in both body and space fixed coordinates. This is possible because

Ref 2. Goldstein, Herbert - Classical Mechanics, Addison Wesley Press, Cambridge 1953

Ref 3. Slater, John C. and Frank, Nathaniel H. Mechanics, McGraw Hill Book Co., New York 1947

$$\vec{L} = I_1 \vec{\omega}_1 + I_2 \vec{\omega}_2 + I_3 \vec{\omega}_3$$

so that $\vec{L}$ can be formed from different amounts of $\vec{\omega}_1$, $\vec{\omega}_2$, and $\vec{\omega}_3$, depending on the I's and the orientation of the body.

Until otherwise stated, from now on only the symmetric case $I_1 = I_2$, will be considered. The ellipsoid becomes a figure of revolution, the 3 axis being the symmetry axis. In this case, Fig. C-1 shows that the 3 axis precesses in a circular cone of half-angle θ , while $\vec{\omega}$ precesses in a circular cone of half-angle $\theta - \beta$.

This is the same motion as is obtained if the body is represented by a cone (Ref. 3) of half-angle β rolling around a space cone of half-angle $\theta - \beta$ with vertices coinciding as shown in Fig. C-2. This representation will be used later. Figure C-2 also shows the vector $\vec{\omega}$ resolved into $\vec{\dot{\varphi}}$, the precession rate, and $\vec{\dot{\psi}}$, the rotation rate relative to a plane through $\vec{L}$ and the 3 axis.[5] The notation ψ , φ , and θ refers to Euler angles (Ref. 2, p. 107, or Ref. 3, p. 108). The quantities in Fig. C-2 are related through the moments of inertia by (Ref. 3, p. 112)

$$\dot{\varphi} \cos \theta = \frac{I_3}{I_1} \omega_3 \qquad \text{(C-1)}$$

$$\dot{\psi} = \frac{I_1 - I_3}{I_1} \omega_3 \qquad \text{(C-2)}$$

where $\omega_3 = \dot{\psi} + \dot{\varphi} \cos \theta$. For Explorer I, $\dot{\varphi}$ and ω_3 were observed directly from intensity fluctuations in the radio signals. Knowing these, Eq. (C-1) relates θ to the moment of inertia ratio.[6]. Using the triangles of Fig. C-2, it is easily shown that

$$\tan \beta = \frac{I_3}{I_1} \tan \theta \qquad \text{(C-3)}$$

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[5] The distinction between $\dot{\psi}$ and $\dot{\psi} + \dot{\varphi}$ is analogous to solar and sidereal time; respectively.

[6] Eq. (C-1) applies to nearly rigid bodies also.

For Explorers I and III, I_1/I_3 was about 75. In this case, Eq. (C-3) shows that β is a small angle until the satellite tumbles to an angle θ very near to 90 deg (arctan 75). This checks with Fig. C-1 for the case in which the major axis is 8.7 times ($\sqrt{75}$ x) the minor axis. Since the last few degrees of rubmling are not very interesting, the approximation $\beta <<$ 1 radian will be used.

Nearly Rigid Body Motion

If a body is nearly rigid, the effects of frictional parts will be very small during one period of precession $(2\pi/\dot{\varphi})$. Therefore, the rapid motion will still be described by the rolling ellipsoid of Fig. C-1. The only remaining part of the description of motion which may be changed by friction is the spin rate and the parameters which describe the cone of precession; that is, the cone of half-angle θ, which the 3 axis traces out.[7] Since there are no external forces, the vector $\vec{L}$ is constant. Therefore, the orientation of the precession cone does not change, since its axis is parallel to $\vec{L}$. This leaves only θ and ω to change, but ω is determined by the constant magnitude of L when θ is given, the equations being

$$L_3 = L \cos\theta = \omega_3 I_3 \qquad \text{(C-4)}$$

$$L_1 = L \sin\theta = \omega_1 I_1$$

Thus, θ is the only quantity for which an equation of motion must be found and integrated. It is also a convenient quantity, since it is the most obvious one to measure when looking at a precessing body.

For the important case in which θ is initially zero, and ω initially ω_0, it is convenient to express ω_3 in terms of ω_0, and θ. By Eq. (C-4).

$$\omega_3 = \frac{L\cos\theta}{I_3} = \omega_0 \cos\theta \qquad \text{(C-5)}$$

[7] Looking at Fig. C-2, one might think both body and space cones can change angle, but these are related by Eq. (C-3). It can be seen in Fig. C-1, that there is no problem because β and θ are related by the shape of the ellipsoid which does not change permanently, although it does vibrate slightly as the frictional part moves.

Substituting Eq. (C-5) in Eqs. (C-1) and (C-2) gives

$$\dot{\varphi} = \frac{I_3}{I_1} \omega_0 \tag{C-6}$$

$$\dot{\psi} = \frac{I_1 - I_3}{I_1} \omega_0 \cos\theta \tag{C-7}$$

Note that $\dot{\varphi}$ is a constant of the motion. For Explorer I this is confirmed by radio data.

A first-order differential equation for θ is found simply by conserving energy and momentum. The kinetic energy T may be expressed in terms of L and θ as

$$T = \frac{L_1^2}{2I_1} + \frac{L_3^2}{2I_3} = \frac{L^2}{2}\left(\frac{\sin^2\theta}{I_1} + \frac{\cos^2\theta}{I_3}\right) \tag{C-8}$$

The only variables in Eq. (C-8) are T and θ. The quantity T decreases as energy is dissipated, changing θ, at a rate given by the derivative of Eq. (C-8).

$$\frac{d\theta}{dT} = \left(\frac{dT}{d\theta}\right)^{-1} = \left[\frac{L^2}{2} \sin 2\theta \left(\frac{1}{I_1} - \frac{1}{I_3}\right)\right]^{-1} \tag{C-9}$$

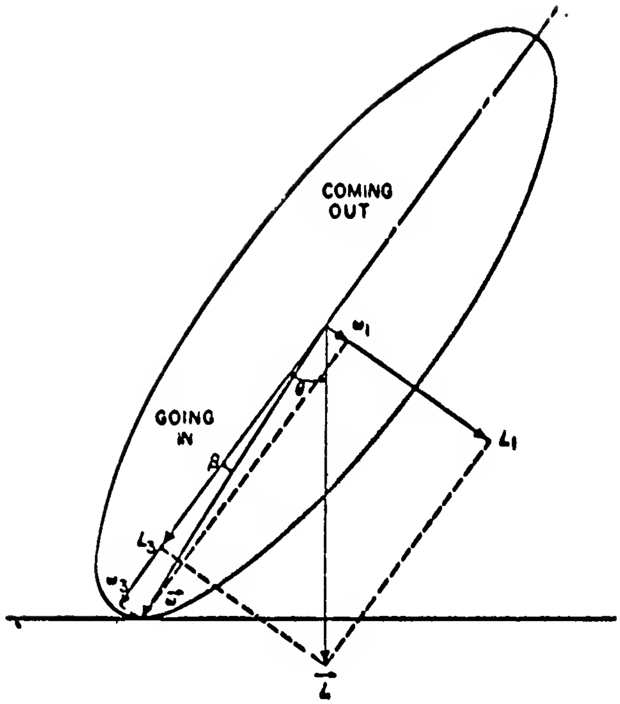
Since T decreases, Eq. (C-9) says that θ increases if $I_1 > I_3$ and θ decreases if $I_3 > I_1$. In both cases, $\vec{\omega}$ tends toward the axis of largest moment of inertia. In other words, the spin of a saucer-shaped body is stable, but that of a cigar-shaped nearly rigid body is unstable and changes to a tumbling[3] motion.

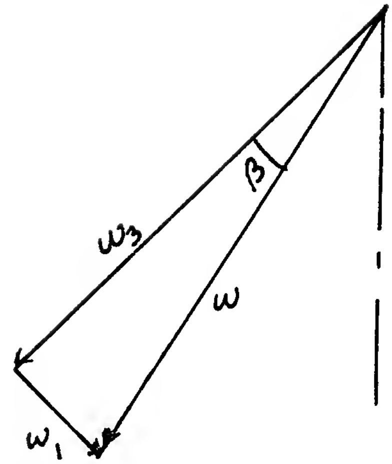
To form the differential equation in terms of θ only, one can substitute Eq. (C-9) into the identity

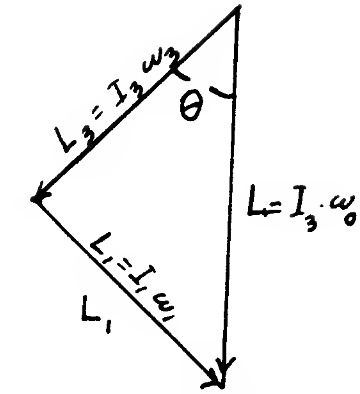
$$\frac{d\theta}{dt} = \frac{d\theta}{dT} \frac{dT}{dt}$$

obtaining

$$\frac{d\theta}{dt} = 2 \frac{dT}{dt} \left[L^2 \sin 2\theta \left(\frac{1}{I_1} - \frac{1}{I_3}\right)\right]^{-1} \tag{C-10}$$





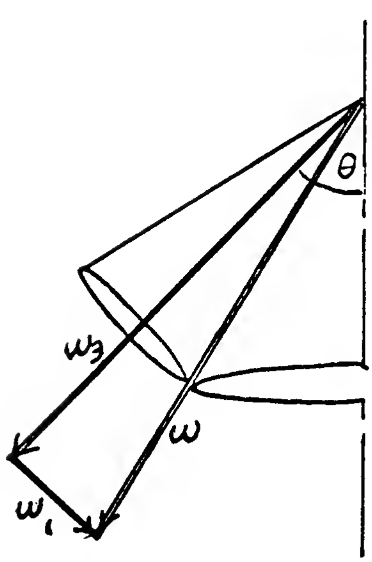


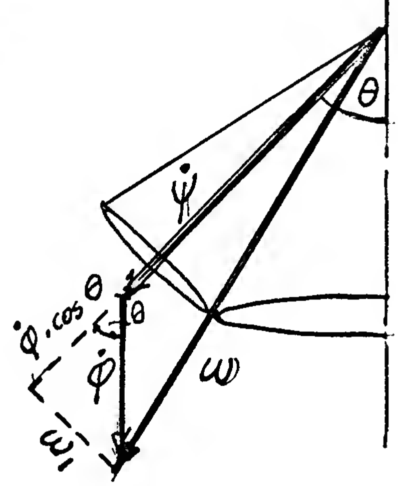
$$L_3 = I_3 \omega_3 = L \cdot \cos\theta$$

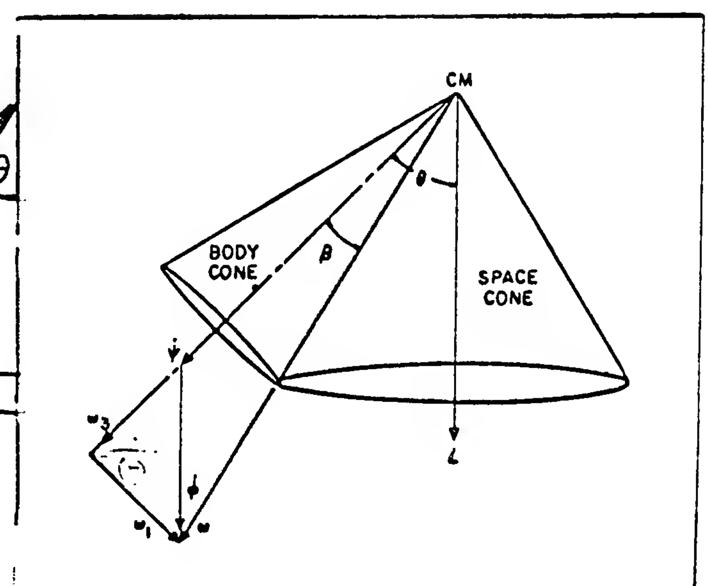
$$L_1 = I_1 \omega_1 = L \cdot \sin\Theta$$

$$\tan\beta = \frac{\omega_1}{\omega_3}$$

Fig. C-1. Rolling Ellipsoid of Inertia







$$\omega_3 = \dot\psi + \dot\varphi \cdot \cos\theta$$

Fig. C-2. Rolling Cone Representation

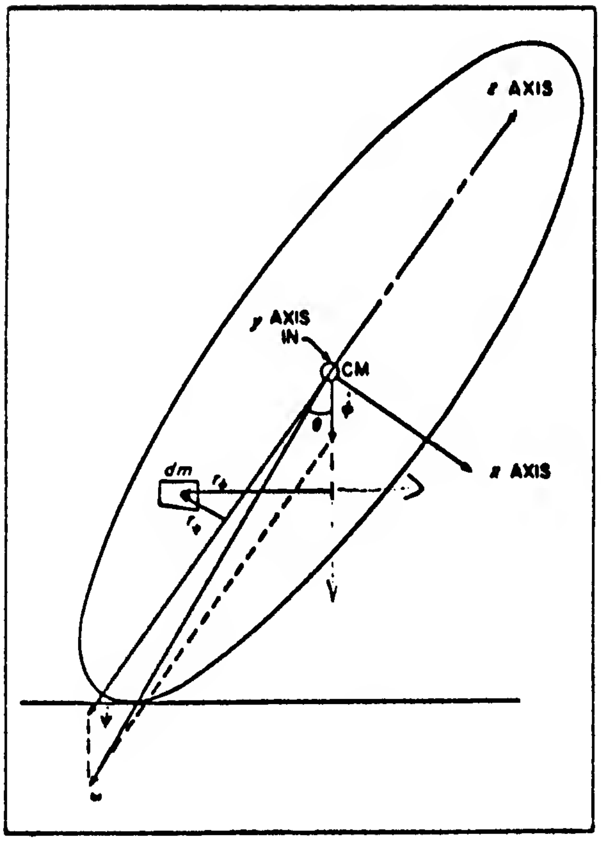


Fig. C-3. Coordinates in Ellipsoid of Inertia

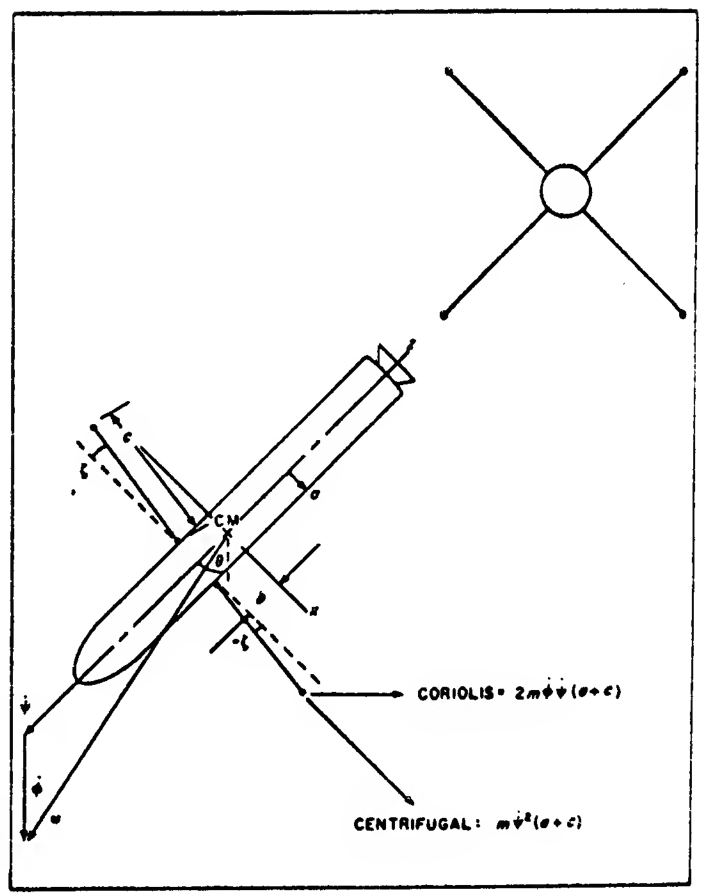


Fig. C-4. Explorer I

Problem II-1: (a) Compute the kinetic energy as a function of the half-angle θ of the precession cone

(b) Compute the rate of energy dissipation as a function of time for Explorer III, from the data shown in Figure I-8.

Problem II-2: (a) How would you determine in the laboratory the rate of energy dissipation of the four antenna wires in Explorer I?

(b) How would you determine in the laboratory the rate of energy dissipation of Explorer III:

(c) How would you estimate the order of magnitude of energy dissipation for a new design?

Problem II-3: Verify equations C-1, C-2, and C-3.

Problem II-4: How would you redesign the Explorer so that it would spin stably about the axis of rotation? What would you specify as the ratio of moments of inertia $\frac{I_1}{I_3}$?

Problem II-5: Suppose you had a satellite spinning about the axis of maximum moment of inertia. How would you engineer a "wobble damper" to reduce the wobble to a minimum? What is the minimum degree of wobble that you would be willing to guarantee to the customer (NASA)?

PART III: OTHER INTERESTING DYNAMICS PROBLEMS ASSOCIATED WITH THE EXPLORER SATELLITE

A. Coupling of Whirl Vibration of Explorer Cluster with Bending Vibration of Launch Vehicle

In order to achieve the desired accuracy of injection of the Explorer satellite into its orbit it was decided that the cluster of stages II, III, and IV should be prerotated to an angular velocity of 750 rpm before launching stage II. In principle this could have been accomplished just before burn-out of stage I either by a spin-up rocket or by an electric motor system. From the standpoint of reliability it was decided to prerotate the cluster with an electric motor drive, while the rocket was still sitting on the launching pad and to keep the angular velocity adjusted by an rpm governor.

The natural bending frequencies of the Redstone booster were computed as a function of flight time. These natural bending frequencies increase as the propellants are consumed. The natural frequency of the first bending mode remains below the cluster rotational speed at all times. The natural frequency of the second bending mode, however, at $t = 134$ seconds passes through 12.5 cycles per second, which is the spin frequency of the Explorer cluster. The time rate of change of this second mode frequency is more than 1/4 cycle per second.

Problem III-1:

The DeLaval steam turbines have demonstrated for more than 50 years that it is feasible to have a rotating system pass through a critical speed.

What analysis or tests would you recommend to make a decision whether it is safe to have the rocket prespun at 750 rpm and to have the bending frequency pass through the frequency of 12.5 cycles per second.

Solution to Whirl Vibration Problem:

The solution which was adopted for the Explorer system is described in ref. III-1 as follows:

"The procedure for cluster run-up is as follows:

Prior to launching, the tub is rotating at 550 rpm. The missile takes off when this speed has been attained. About 70 seconds after take-off, a governor controlled by tape programmer inside the missile changes the regulator setting gradually up to 650 rpm. At 115 seconds after take-off, it rises to 750 rpm. Thus while the first-stage flight is in progress, the rate of spin slowly accelerates.

This procedure was selected to avoid resonance between the spin frequency of the cluster and the bending frequency of the booster. This bending frequency changes as propellants are consumed. The rpm must be kept down to 550 so long as the tanks are full and the bending frequency is correspondingly low. Only after the booster has consumed a substantial volume of propellants can the spin frequency be increased. The increase is about proportional to the increased bending frequency. At no time in flight is a critical frequency experienced.

About 20 seconds before cut-off, the maximum spin rate of 750 rpm has been reached. There is no change in it during the free coasting climb to apex."

In a later memo Dr. von Braun commented that in view of the high rate of passing through the critical frequency detrimental coupling would probably have been precluded. He decided, however, to adopt the above described more conservative approach.

Reference III-1: W. von Braun, The Explorers, Astronautica Acta, 1959, pp. 136-137

Footnote:

In 1959 a Lockheed Electra airplane crashed after disintegrating in flight. In 1960 a similar Electra crash occurred and all Electra airplanes were grounded until these flight failures were explained. An exhaustive structural and dynamic investigation was made into these failures. The NASA report on the investigation* concluded that this failure was due to a coupling of the natural bending-torsional vibration of the wing with the propeller rotational motion on the outboard nacelle. The mystery with this Electra vibration was why this phenomenon should

B. Increase of the Spin Rate by Rocket Exhaust

In Reference I-2 W. C. Pilkington describes the variation in the spin rate during the boost phase as follows:

"The spin data on the Explorer III launch is contained in Fig. III-1. Note that the spin rate was approximately 12.7 rps during the entire coast period. Stage 2 ignition did not change the spin rate; it was continuous through stage 2 burning and stage 2 coast at 12.7 rps. No points were available during the stage 3 burning, but a good point is available during the coast period between stage 3 burnout and stage 4 ignition. The dotted lines show a rapid decrease on stage 3 ignition, but the spin could have varied in several other ways. At stage 4 ignition the spin apparently decreased to approximately 10 rps. One fairly poor point just after the start of burning gave a value of 9.8 rps. After burnout many points are available at 10 rps. The rate did not change during the rest of this record. Explorer III had no transient similar to that of Explorer I, and Explorer III went sucessfully into orbit, although there was a small angular error on injection (end of burning of stage 4).

The spin record of the Explorer IV launch phase is shown in Fig. III-2. The spin was constant at 12.5 rps during the coasting phase before stage 2 ignition. Upon stage 2 ignition the spin remained sensibly constant and only changed upon ignition of stage 3. Several points imply that the spin changed from approximately 12.5

Footnote (continued)

be found only after more than 80,000 hours of successful flight operations of the Electra airplanes. This was resolved finally by experimental tests of a dynamically similar model in a NASA wind tunnel. It was known that the Electra which had crashed had experienced a hard landing earlier. By simulating damage in the outboard nacelle such as might occur after a hard landing the wind tunnel model demonstrated that coupling could develop between the propeller rotation and the wing oscillation. This combined bending - whirl mode built up over a period of 20 to 40 seconds from inception to destruction of the wing.

The fix consisted in a major stiffening of the wing and engine mount structure to avoid any possibility of coupling of the propeller whirl mode with wing bending or torsional vibrations. These modifications were carried out on all existing Electra airplanes, and the airplane has had an excellent safety record since then.

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*Reference III-2: Robert J. Serling - The Electra Story, Doubleday and Company - page 81

to about 11.9 rps at stage 3 ignition and remained relatively constant during the burning of stage 3 and the coast following it. Upon ignition of stage 4 the spin decreased to approximately 10.5 rps and then increased slowly to approximately 11.2 rps at the burnout of stage 4. The spin then remained constant to the end of the launch pass. The reasons for the apparent decreases upon ignition are not completely understood, nor are the exact reasons for the increase during the burning understood. However, it is certainly easy to visualize possible reasons for each of these. An example of a reason for decrease might be some interference on the launching apparatus as the stages separate. A possible reason for the slow change during burning is the following: the gases going out of the nozzle have angular velocity relative to the nozzle since the radius at which the gases are generated is different from the nozzle radius, and this transfers angular momentum to the nozzle, changing the spin of the stage."

Fig. III-3 shows that Explorer I experienced a similar increase in spin rate during the burning period, as Explorer IV.

Problem III-2:

When a rocket undergoes longitudinal oscillations find the magnitude of the "damping force" due to the jet exhaust.

Suggestion: Consider a rocket mounted on a whirling arm rotating at a uniform velocity. The rocket fires radially outward. Compute the torque required to keep the whirling arm rotating at a constant velocity from the time rate of change of the angular momentum in the discharged rocket gases.

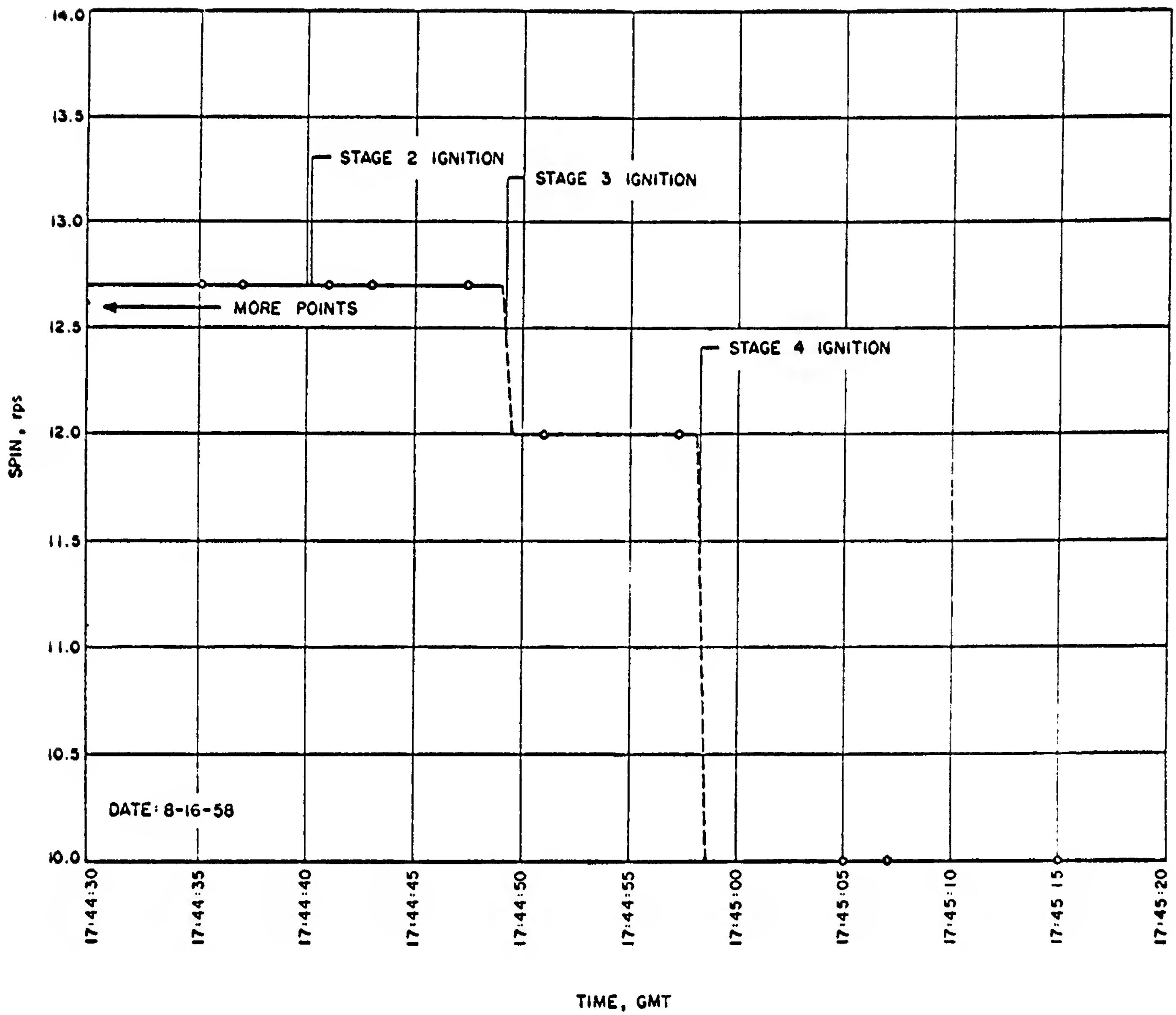


Figure III - 1. Plot of Spin Rate vs Time for Explorer III During High-Speed Staging

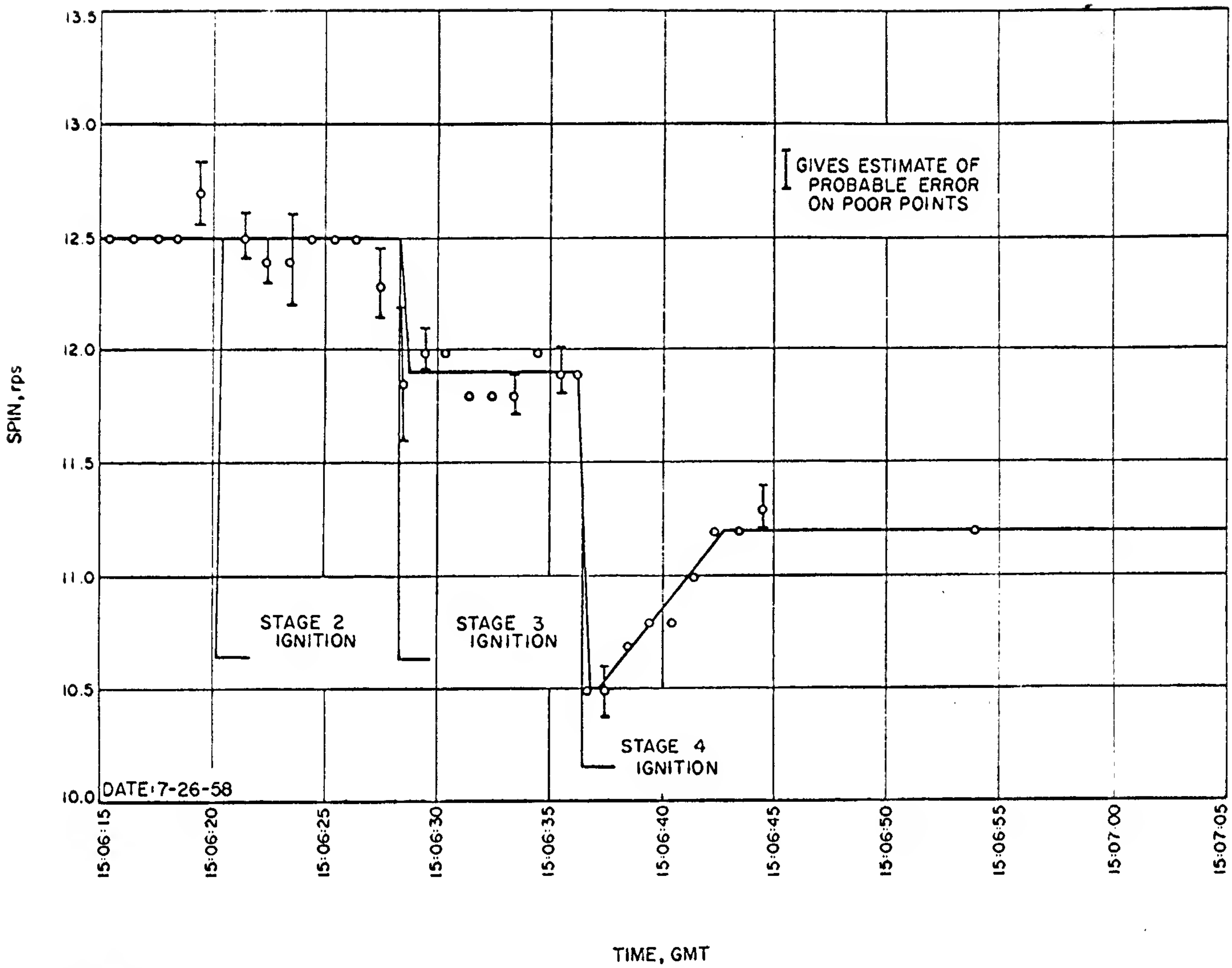


Figure III - 2. Plot of Spin Rate vs Time for Explorer IV During High-Speed Staging

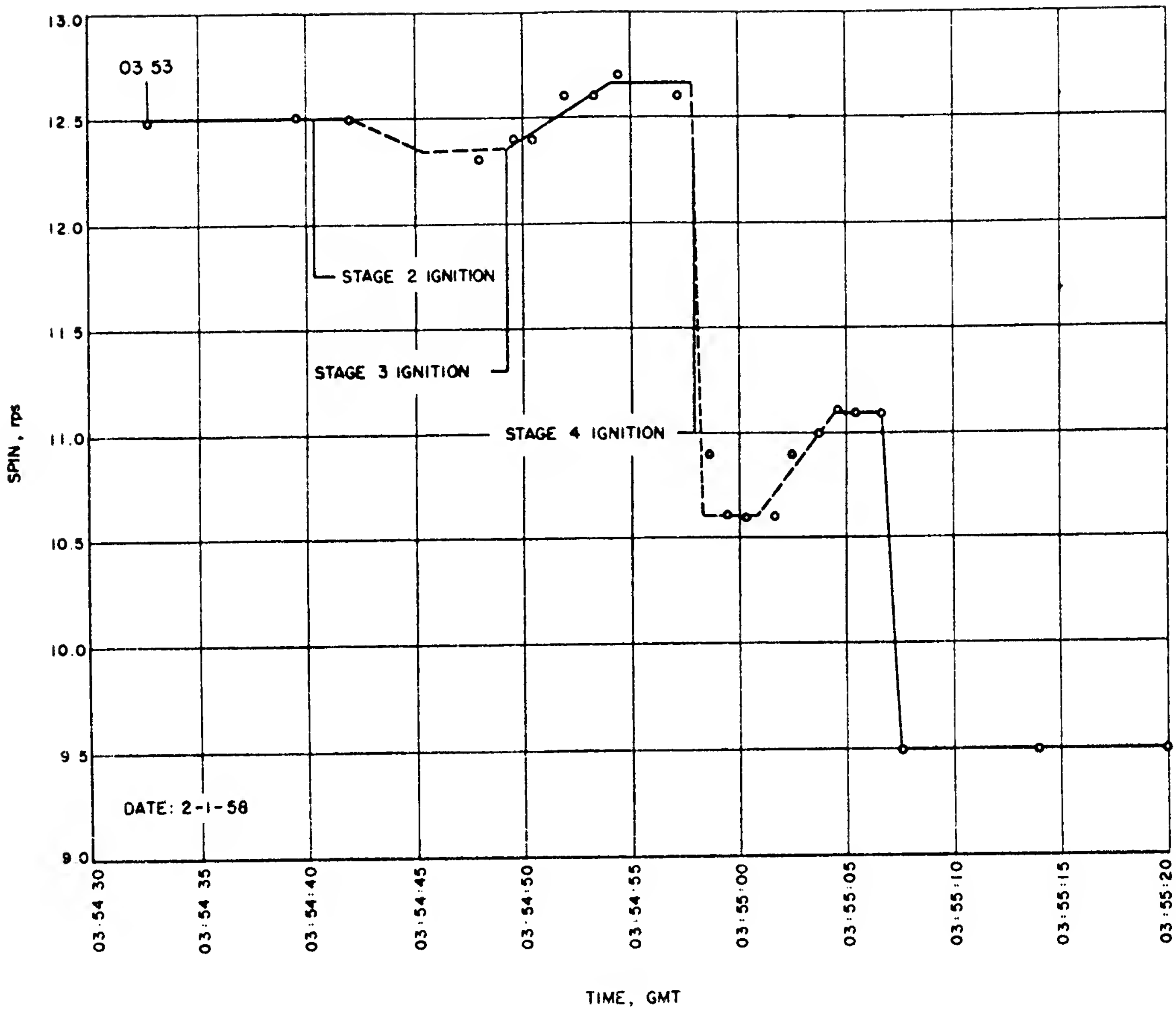


Fig.III-3. Plot of Spin Rate vs Time for Explorer I During High-Speed Staging

Problem III-3:

(a) Fig. III-4 and the table below present descriptive data on the Explorer IV fourth-stage motor. How would you explain the increase in angular velocity of the Explorer rocket during burning? How is this additional angular momentum physically transferred from the propellant to the motor case?

(b) It is reported that for some spinning rockets the angular velocity decreases during burning. How would you explain this phenomenon?

(c) What would be the effect of jet damping (as discussed in problem III-2) upon the precessional motion of a rocket.?

Table: Principal Data on Explorer IV Fourth Stage Motor:

Length (overall, including nozzle)	46.5 inches
Diameter (excluding thrust and attachment fittings)	6.00 inches
Weight (loaded)	61.44 pounds
(after burning propellant)	11.91 pounds
Effective thrust (80°F)	2015 pounds
Effective burning time (80°F)	6.08 seconds
C.G. location from head end-loaded	20.6 inches
-empty	25.7 inches
Nozzle expansion angle	30 degrees
Effective head end pressure	618 psia
Total impulse	12250 pounds-seconds
Effective specific impulse	249 seconds

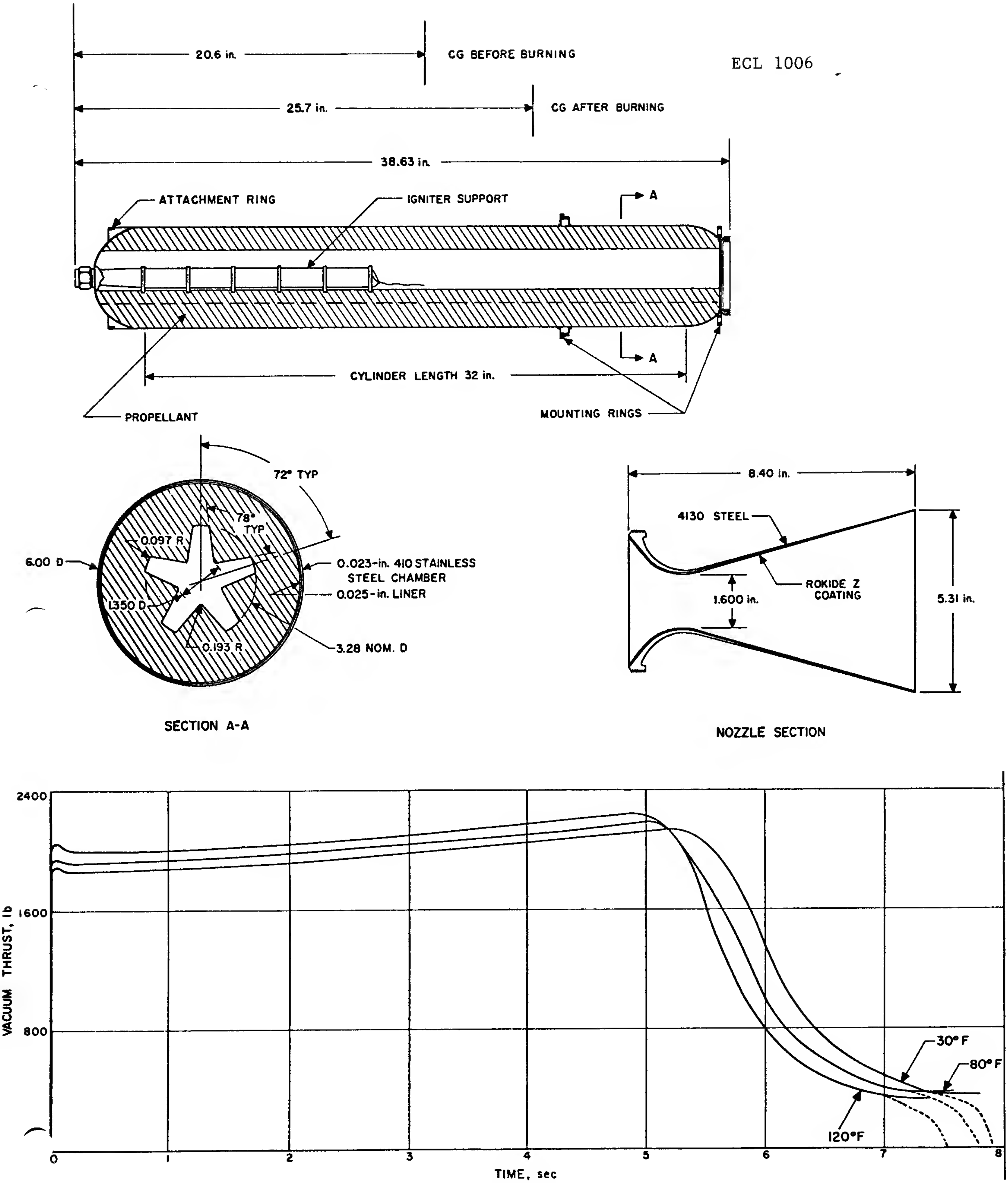


Fig. III-4. Explorer IV Fourth Stage Motor

PART IV: HISTORICAL BACKGROUND OF EXPLORER, THE FIRST U. S. SATELLITE -- by William Bollay

In the early 1950's I had started my own company, the Aerophysics Development Corporation and I served as President and Technical Director. One of the fields which interested me personally was hypersonic aerodynamics. Since our small company could not afford a wind-tunnel I looked into the possibility of building a small hypersonic test vehicle. I was pleasantly surprised to find that this appeared feasible by assembling a cluster of small solid propellant rockets, the LOKI, into a two stage rocket which we called the HTV (Hypersonic Test Vehicle). The Air Force supported the development of the HTV, and we initiated a test program firing first a single stage, then a two-stage, and finally a three-stage cluster of these rockets.

During a visit to Redstone Arsenal in the spring of 1954 I mentioned to Dr. von Braun this interesting and very simple method of achieving hypersonic speeds. At that time, Dr. von Braun was the Technical Director of the Guided Missile Development Division at Redstone Arsenal in Huntsville, Alabama, where the Redstone and Jupiter Missiles were being developed. I reported that we could attain an increase of velocity of about ΔV = 5000 ft/sec per stage (neglecting drag), so that a three stage version should be able to attain about ΔV = 15, 000 ft/sec in a vacuum. He became very much interested at this point and explained that the Redstone booster would be able to achieve about 10, 000 ft/sec and by taking advantage of earth rotation (about 1500 ft/sec) the REDSTONE plus our three stage solid-propellant cluster would therefore be able to exceed the minimum velocity required for an artificial earth satellite (25, 591 ft/sec.)

We agreed to study this combination in more detail. With Dr. von Braun's support the Office of Naval Research in Washington agreed to sponsor a study contract by the Aerophysics Development Corporation for "Project Orbiter", and the Redstone Missile Organization (supported by the Army Ordnance Department) studied the modifications necessary in the REDSTONE missile to carry our cluster-rocket payload. Our joint studies confirmed that we should be able to accelerate a five pound instrument payload to the satellite velocity. We could not, however, carry the weight of a guidance and control system on the small solid propellant rockets. We therefore proposed to use the "Poor Man's Stabilization System", i.e., a spinning rocket cluster. We proposed that a spin table be installed

on top of the REDSTONE missile to provide a prespin to the solid propellant clusters before they were fired. Thus any small differences in the thrust level and burning time of the individual rockets would be averaged out.

The Aerophysics Project Engineer on this study was Mr. James B. Kendrick. He carried out the detailed design and performance studies. He studied a numb er of alternate designs including clusters of Loki II rockets, and clusters of 6 inch or 7 inch scaled down Sergeant rockets. He showed that it was feasible to aim the cluster accurately enough by balancing the cluster very precisely in a spin-up test stand and then spinning the cluster prior to launching from the REDSTONE· Dr. Nils O. Myklestad performed the dynamic analysis of the dispersion of the spinning satellite as a function of the small differences in thrust and burning time of the individual rockets.

The feasibility studies at Aerophysics on this project "Orbiter" progressed very satisfactorily. They were reviewed and checked by the Jet Propulsion Laboratory of Cal. Tech. and by Redstone Arsenal, and it was planned to prepare for a satellite firing in the fall of 1956. Unfortunately, in August 1955, the committee involved in planning the IGY Satellite Program recommended termination of our small and low cost Project "Orbiter" and instead proposed to start a brand new satellite project -- namely, Vanguard. As a result of this adverse recommendation Project "Orbiter" was terminated.

Fortunately the Guided Missile Development Division at Redstone Arsenal decided to continue the development of the concept of "spinning clustered solid-propellant rockets for upper stages" toward a slightly different objective. By replacing the last of the three solid propellant stages with a model nose-cone this cluster was adapted to study the problem of ballistic reentry. Inhouse studies on clustered upper stages, and on their integration with Redstone Missiles, we re initiated at Redstone Arsenal and at JPL; they resulted in the development of a high-speed test vehicle capable of generating the high velocities encountered by re-entering Jupiter warheads. This high-speed test vehicle was named "Jupiter C". Our Aerophysics Development Corporation developed the "Rocket Cluster Assembly and Test Stand" which was used very successfully for checking the balance of the satellite clusters on the Jupiter C firings. The first Jupiter C re-entry vehicle was successfully launched on September 20, 1956. It was a test vehicle similar to the earlier "orbiter" configuration, except that the fourth stage carried an inert ballast instead of propellant. The first successful nose cone flight for missile reentry took place on August 8, 1967.

On 4 October 1957 the Soviets successfully launched the first SPUTNIK. This event caused considerable discussion in the world's press. The Vanguard satellite program had been delayed, as described in Appendix A. Drew Pearson in his column of October 25, 1957 gave the first report on project "Orbiter" and its cancellation (Appendix B). Finally on Nov. 8, 1957 the Secretary of Defense announced that the Army was to participate in the IGY satellite program. In just 84 days from the announced authorization on January 31, 1958, Explorer I, the free world's first satellite was successfully orbited.

The background story on the Orbiter-Explorer decision was presented fairly accurately in U. S. News and World Report of Nov. 22, 1957 (Appendix C).

The technical aspects of the Explorer development are presented in Appendix D and reference IV-1.

Ref. IV-1: W. H. Pickering, History of the Juno Cluster System - Astronautical Engineering and Science, McGraw Hill (1963)

APPENDIX A

TROUBLES BOOST VANGUARD COST

Washington - Additional $34.2 million requested by Navy from Defense Department funds for completion of Project Vanguard was made necessary partly by developmental troubles with first and second stage engines and the satellite launching vehicle itself. All three now have been corrected.

Rear Adm. Rawson Bennett, Chief of Naval Research, explained to a House subcommittee that only three things can be adjusted "whenever you run into any kind of trouble in a development project" - money, time and performance.

Solution With Money

"We are not at liberty to change either the time or performance, so we have to use money to get out of trouble."

The troubles were:

- General Electric Co. first-stage engine. "It seemed to burn out," Adm. Bennett said. "...The real answer was quality control; the nozzles, the injectors and other items were not being accurately enough made so that unusual heats, that is, local heat spots in the engine, would be prevented. Once that was realized and corrected the first-stage engine was on the beam"

- Aerojet-General Corp. second-stage engine. This engine "was in a similar sort of trouble." Adm. Bennett said. "The source or reason for the trouble was also unknown. It eventually turned out to be a somewhat similar type of defect and was corrected."

- Martin Co. launching venicle. "The structural trouble was the computational suspicion that vibration, etc., would set in within the vehicle frame," Adm. Bennett said. "This was eventually ironed out but at considerable time and expense for recomputation and re-engineering. We did not lose any particular fabrication time or energy, only the money in correcting the defect."

Total Cost

Total estimated cost of the Vanguard program, including the $34.2 million, is $110 million. Capt. A. B. Metsger, Deputy Chief of Naval Research, told the Senate Appropriations Committee that "if we do this by the end of 1958 for $110 million, this

will be the quickest and cheapest rocket project that has ever been seen, and I think we may well do it. This is a bargain-basement job."

Adm. Bennett cited two other factors contributing to rising Vanguard costs. which Rep. George H. Mahon (D-Tex.) said had "ballooned heavenward to a pretty high point."

· "When the scientists discovered that they could not just simply take items off the shelf, put them together and have a successful satellite."

· "When the detailed specifications were written, and for the first time everyone realized the full implications of the development work involved."

Martin Co., prime contractor on an installment type cost plus fixed fee contract, has estimated committed costs to date to be $47,581,000. Navy said, Original estimate in March, 1956, was $28,649,000.

Test Program

Other highlights of the Navy testimony:

· Second test firing last May, using a Viking rocket plus Vanguard third stage prototype, "proved beyond a shadow of a doubt the essential soundness of the design for separation and spin stabilization of the Vanguard third stage." Adm. Bennett also said proving the fact "that the rocket would ignite and burn satisfactorily at this altitude (was) successfully accomplished."

· First Minitrack station, now in operation at Blossom Point, Md. "has been receiving signals from celestial bodies since last fall. This station recently picked up signals from the moon."

· Some Vanguard rocket instrumentation and the Minitrack transmitter "performed successfully" in the first test firing last December, using a single stage Viking rocket.

· Total of two Vikings and five Vanguard test vehicles will have been fired before first of six Vanguard launching vehicles is fired (see p. 86).

· Instrument packages for first few satellites now are fairly firm. Package I will include devices for measuring atmospheric environment and solar ultraviolet radiation. Package II will measure cosmic rays. Package III will measure the earth's magnetic field and aerodynamic drag on the satellite. Package IV will be either a meteorological experiment or investigation of the earth's radiation balance.

APPENDIX B

Washington Post - Oct. 25, 1957

Washington Merry-Go-Round — Drew Pearson

SIX SATELLITES UNDER WRAPS

Washington - One of the unpublished facts about the American "Sputnik" snafu is that the Army has six satellites in a warehouse in Huntsville, Alabama, all ready to launch. They could have been launched before the Sputnik, thus keeping the U. S. A. ahead of the U. S. S. R. in science, and preventing one of the greatest psychological defeats the United States ever suffered.

But for some strange and mysterious reason, difficult to fathom, the Army was under orders not to launch these satellites.

About three months ago, the Budget Bureau, which operates directly under the White House, actually sent auditors to the Army's Redstone Arsenal at Huntsville, to make sure the Army did not spend a nickel on the satellite program.

All Complete

The six satellites now gathering cobwebs in a Huntsville warehouse, are complete with fibreglass, radio transmitter and gyro mechanism. They are elongated in shape, nicknamed by the Army the "Baseball Bat".

In trying to track down the reason why these satellites were sidetracked, this column ran into rigid government censorship. Every official connected with the military phase of the satellite program has been ordered not to talk to the press.

MYSTERY OF THE SIDETRACKED SATELLITE

The Documented Story of a Decision That Gave Russia the Edge

Nine years ago the U. S. began planning to launch an earth satellite.

First, the Army got the job. Later, the Navy and Air Force were brought in. Now, the Army has been told to go ahead full speed.

Delays occurred. U. S. still has no satellite. Step by step, for the first time, you learn here the full story of how Americans let the Russians win the race into space.

The decisions, the hesitations, the cancellations are fitted together from official papers, and reports from former officials.

These are facts that investigators in Congress will look for—told to you now.

Exactly what happened to cause the United States to lose out to Soviet Russia in launching the first earth satellite? When was the decision made that gave the Soviet Union its chance to capture the imagination of the world? Who made that decision, and why?

These are questions widely asked. Leaders in Congress are getting set to dig out the answers through investigations soon to get under way. These Congressmen express chagrin and bewilderment over the question of why this country lost a race that easily could have been won.

The answers—how the Russians got into the race, what the U. S. did—are given in the report that follows. This report is based upon documents and statements, and upon interviews with officials and scientists involved in the whole venture from its start.

The report begins with the first known official U. S. document to mention launching of a satellite with a guided-missile rocket, nearly nine years ago. It continues to Nov. 8, 1957, when the Army was ordered to use its Jupiter-C rockets to launch cylindrical satellites as soon as preparations can be completed. This latest order to the Army goes full circle back to the original plan to put up a satellite with the Army rocket by summer or early autumn of this year, ahead of the Soviet Sputnik—but the Army was shunted aside. How and why is part of the story told here.

—Wide World

FORMER RESEARCH DIRECTOR QUARLES AND FORMER SECRETARY WILSON
A panel in the Pentagon made the choice between competing satellite plans

First Clue—1948

December, 1948. The first clue that the U. S. was working on a satellite came at this time in the annual report of the late James Forrestal, Secretary of Defense. The report said:

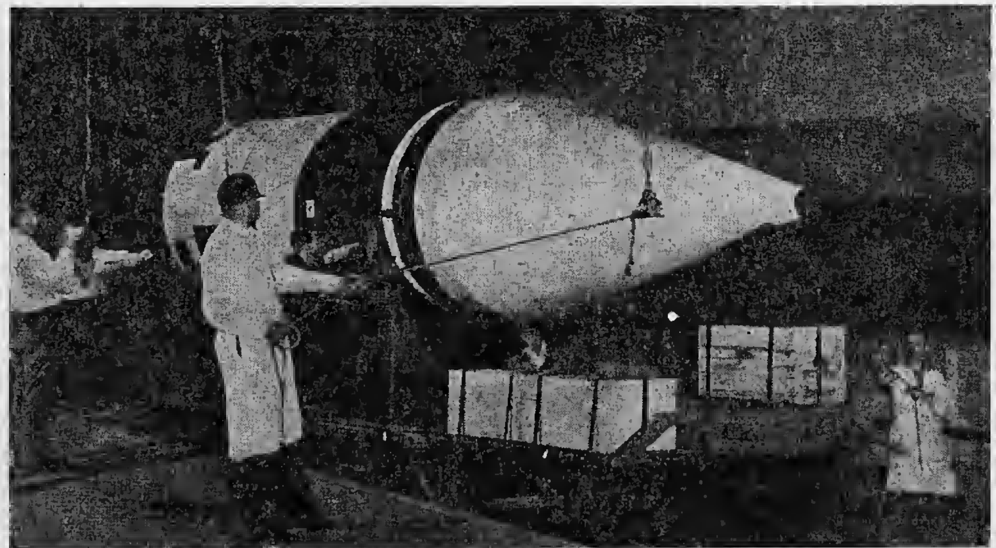
"Guided missiles.—The Earth Satellite Vehicle Program, which was being carried out independently by each military service, was assigned to the Committee on Guided Missiles for co-ordination. To provide an integrated program with resultant elimination of duplication, the committee recommended that current efforts in this field be limited to studies and component designs . . ."

It was more than five years later tha. the first specific plan to send up a satellite crystallized, in June, 1954. Step by step, from that time to the present, th story unfolds.

A report made in February, 1956, b an officer of the U. S. Navy, tells how the first satellite project was born—and died.

June 25, 1954—On this date, in Room 1803, T-3 building of the Office of Naval Research in Washington, military and civilian scientists planned the first launching. Leaders in this group were Dr. Wernher von Braun, German-born rocket scientist from the Army's missile center; Fred Durant, president of the International Astronautical Federation; Dr. Fred Whipple, astronomer and long-time scientific adviser to the armed services; Dr. S. Fred Singer, an adviser on rockets and missiles, and Commander

MISSILEMAN VON BRAUN
. . . with Redstone model



—USN&WR, Chrysler Corporation Photos

NOSE OF A REDSTONE ON THE PRODUCTION LINE
The Army planned to use the rocket to launch a satellite

George W. Hoover, Office of Naval Research.

This group agreed upon the Army's Redstone rocket, capped with a Loki rocket for its second stage, as a combination that could throw a satellite into an orbit at least 200 miles from the earth without new major development."

A satellite of about five pounds could be put up quickly, a larger, better-instrumented one soon afterward, they believed, if an official project, with Army participation, could be set up.

Rear Adm. Frederick R. Furth, then chief of Naval Research, approved the idea, authorized an approach to Army missile directors at Redstone Arsenal in Alabama.

Aug. 3, 1954—Navy officers and scientists conferred at Redstone Arsenal with Dr. Von Braun and Maj. Gen. Holger N. Toftoy, commander of the Redstone base. As a result, the Chief of Army Ordnance, Maj. Gen. Leslie E. Simon, and Admiral Furth agreed upon a project using both Army and Navy facilities to put the ball in space.

At this point, the satellite plan got an official name—"Orbiter." The plan went into high gear.

Jobs were divided. The Army was to design and build the rockets and do the actual launching. The Navy's tasks: build the satellite, set up tracking stations, record the scientific data.

Contracts were let: to Alabama Engineering and Tool Company to make the second-stage rocket mount and guidance system; to Aerophysics Corporation to refine the second-stage rocket; and to the Varo Manufacturing Company to design instruments for the satellite.

Oct. 4, 1954—Another U. S. satellite program was born, in Rome. U. S. scientists attended a meeting there of the Special Committee for the International Geophysical Year—an international scientific group representing some 60 nations, including the Soviet Union.

As a result of suggestions by the American scientists, this group asked nations with rocket capabilities to consider launching scientific satellites during IGY, an 18-month period beginning July 1, 1957. It was this idea that led to the Vanguard satellite plan.

Jan. 20, 1955—Orbiter was still moving along. The Air Force was invited to join and aid in supplying the project and in tracking the satellite.

At this time, the whole plan was submitted to Donald A. Quarles, then Assistant Secretary of Defense for Research and Development. Through Mr. Quarles the plan was to be taken up with Secretary of Defense Charles E. Wilson. A major policy decision of space satellites now was called for.

The Naval Research Laboratory also came into the program and offered its Minitrack devices—the same as are to be used in the current Vanguard project—to track the satellites.

March, 1955—The scientists' idea, now considerably refined, was taken to the White House by Dr. Alan T. Waterman, director of the National Science Foundation. Dr. Waterman did not get to see President Eisenhower; he dealt, instead, with a White House subordinate.

Dr. Waterman asked that the Defense Department provide rockets to put the satellites in space. He said that the Foundation, which is financed by Government appropriations, could pay for the satellites and their instruments.

April 16, 1955—The Russians revealed that they were planning to put up a space satellite. The Soviet Government formed a permanent team of top scientists to "work on problems of mastering cosmic space." The first assignment of this team was to put up a satellite which the Russians said would be "an automatic laboratory of scientific research."

May 23-24, 1955—The Orbiter team gathered for the fifth—and last—time at Redstone Arsenal and Patrick Air Force Base in Florida to see a Redstone rocket fired.

A schedule for the launching was established. Construction of a launching site was to begin in April, 1956; launching of the first ball was planned for midsummer or autumn of 1957.

Spring-summer, 1955—Decision on the rocket-satellite plans was made in the Defense Department. One man who was a high official, close to the President at that time, now says:

"The Orbiter plan never got to the White House or to the National Security Council. This whole thing was settled in the Pentagon."

Assistant Secretary Quarles laid competing satellite programs in the laps of nine top civilian scientists—the Special Capabilities Panel, headed by Dr. Homer J. Stewart, a jet-propulsion expert. One of its members was Dr. Clifford C. Furnas.

Dr. Furnas, now back at his regular job as chancellor of the University of Buffalo, tells how the decision was made.

The panel quickly turned down an Air Force offer of its Atlas rocket be-

[continued]
MYSTERY OF SIDETRACKED SATELLITE

cause it was improbable that the Atlas would be ready soon enough.

Showdown—1955

Final choice was between Army and Navy plans. The Army was in a position to shoot first, with the Redstone rocket. The Navy had better scientific instruments, but its launching rocket, based upon the Viking, would have to be rebuilt, with a bigger motor.

Dr. Furnas says the panel found it impossible to combine the Army's rocket and the Navy's instruments because of service jealousies.

Dr. Furnas and one other panel member voted to use the Army's rocket, to get a satellite up the quickest way. Four panel members preferred the Navy's instrumentation, even though it would mean delay in orbiting a satellite. Three, who said they were not experts on missiles, went along with the majority in favor of the Navy plan. Final vote was 7 to 2.

The split decision was laid before Mr. Quarles. He accepted the plan approved by the majority. Vanguard was born; the Redstone plan died at once.

Atmosphere in the Defense Department, when the decision was made, now is described by one of the nation's foremost scientists, who still helps to direct research vital to future weaponry.

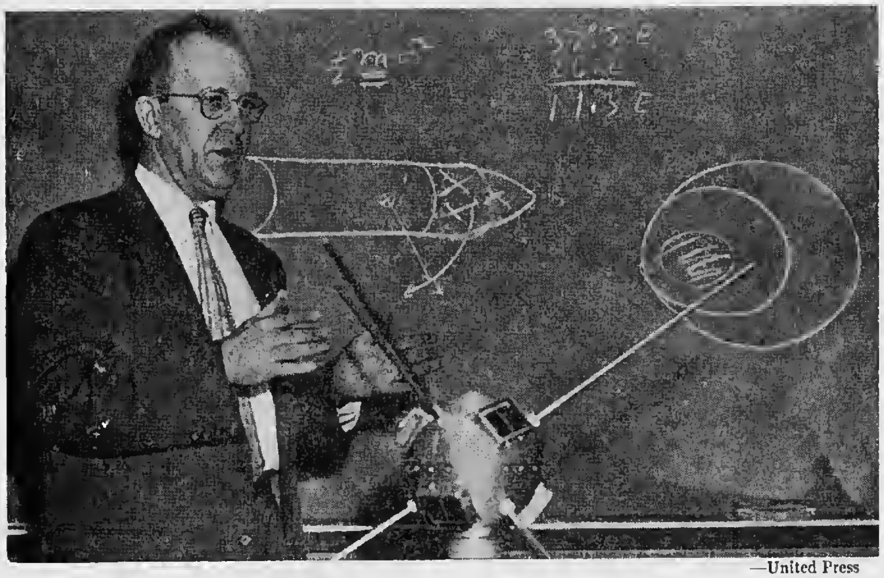
"Charlie Wilson said on more than one occasion that the earth satellite had no scientific interest to the Department of Defense," this scientist says. "This illustrates the lack of understanding of Wilson and some of his people of what research could really mean to the future of the Department of Defense.

"They had this astonishing edict that research must always be tied to existing missions.

"I once told them. I said, 'Look, you've got this upside down. What you should say is that existing missions should be tied to the ideas emerging from research.' "

July 29, 1955—The Government's decision to launch a satellite was made public at the White House by the President's Press Secretary, James C. Hagerty.

Dr. John P. Hagen, a scientist employed by the Naval Research Laboratory, was put in charge of Vanguard.



—United Press

DR. JOHN P. HAGEN, DIRECTOR OF PROJECT VANGUARD
This program is now to be "supplemented" by Army Jupiter-C rockets

Aug. 2, 1955—L. I. Sedov, one of Russia's foremost space scientists, told a scientific convention in Copenhagen, Denmark, what the Russian plans were: to launch a satellite bigger and heavier than the 20-inch, 21-pound instrument contemplated by the U. S. Sedov said the Russians would launch their first "moon" in about two years, in the late summer or autumn of 1957.

The race now was on, at least in the Soviet view.

August, 1955—A few days after the White House announcement, the Vanguard project was started.

Contracts were let. The Martin Company, of Baltimore, builder of the Viking rocket, got the over-all contract for an improved version to launch the satellite.

Subcontracts went to General Electric Company for the first-stage engine and to Aerojet General Corporation for the second-stage engine. Competing subcontracts for the third stage were given to Allegheny Ballistics Laboratory and Grand Central Rocket Company.

December, 1956—A Viking rocket, carrying testing devices, was fired in the first of several tests for the Vanguard launching rockets. At this point, says Rear Adm. Rawson Bennett II, Chief of Naval Research, trouble developed that took time and millions of dollars to overcome.

Admiral Bennett told a House subcommittee that the first-stage rocket motor burned out. "The nozzles, the injectors, and other items were not being accurately enough made."

May 1, 1957—Dr. Richard W. Porter, chairman of a scientific panel on the Vanguard program, told a House subcommittee that the target date for launching the first U. S. test satellite was being postponed. It had been planned for September, 1957. The delay was in providing rockets.

June-July, 1957—The Navy asked Congress for a supplemental appropriation to pay the extra cost of rebuilding the troublesome rocket engines. The amount asked was 34.2 million dollars, running the total for the Vanguard project to 110 million.

Payoff for Russia—1957

Oct. 4, 1957—Russia launched the world's first earth satellite, Sputnik I. A month later, on November 3, Russia launched Sputnik II, containing a live dog and many complex scientific instruments.

Nov. 8, 1957—The new Secretary of Defense, Neil H. McElroy, ordered the Army to use its Jupiter-C test missile to launch scientific satellites as a "supplement" to the Vanguard program. The Redstone rocket, one of the component of Jupiter-C, is a proven engine, nov in production. It is available in nur bers.

The U. S. still has no satellite beepi through space. But, by coming bac' a rocket once shunted aside, offi hope that, even though the U. S. finisl second in the race, it will at least able to match the Russians in numbe of satellites.

Close-up of two men charged with getting U. S. satellite into space, page 98. President Eisenhower—how U. S. will meet challenge of Soviet science, page 114.

Appendix D:

Article published in Astronautica Acta 1959, page 126 to 143

The Explorers[1]

By

Wernher von Braun[2], ARS

(With 10 Figures)

(*Received July 25, 1958*)

Events of the past ten months since this Congress last convened in Barcelona have given special meaning to these meetings of the International Astronautical Federation. History-making demonstrations of advancing rocket technology have focused the attention of people everywhere on the International Geophysical Year and the concerted effort of scientists from all over the globe to obtain more information about our home planet and the open spaces around it.

It is therefore a propitious time for this assembly, which is broadly representative of the scientific and engineering programs of many nations interested in the limitless areas beyond the earth. I believe I speak for all of us assembled here in this room when I say that for many months we felt a deep regret that the International Geophysical Year will be concluded all too soon. We knew in our hearts that it would indeed be tragic if we failed to continue the world-wide research program initiated under the IGY which has rendered mankind such convincing and heartening proof that even in times of tension and crises the world's scientific community can work together for the mutual good. And as protagonists of the grandiose concept of flight into outer space we all knew that it would be an incorrigible mistake and a severe setback for all astronautical endeavors and programs if we failed to make further use of the world-wide network of observation stations established for the IGY effort. It was thus with a feeling of infinite relief and gratitude that we learned that during the recent meeting of the national representatives of the International Geophysical Year in Moscow it was resolved to continue the most important phases of the IGY program through the coming calender year. I strongly recommend that this assemblage exert its good influence to ensure the vigorous continuance of this effort with the objective of providing a continuous permanent basis for a close international cooperation not only in spirit but also in the practical phases of astronautical projects.

As a preamble to my discussion of one portion of the space programs of the United States of America, I quote a statement by President EISENHOWER on March 26, 1958. On that date the President made public a presentation by his Science Advisory Committee entitled "Introduction to Outer Space." In doing so, Mr. EISENHOWER said:

[1] Presented at the IXth International Astronautical Congress at Amsterdam, Netherlands, August 25–30, 1958.

[2] Director, Development Operations Division, U.S. Army Ballistic Missile Agency, Redstone Arsenal, Alabama, U.S.A.

"This statement of the Science Advisory Committee makes clear the opportunities which a developing space technology can provide to extend man's knowledge of the earth, the solar system, and the universe. These opportunities reinforce my conviction that we and other nations have a great responsibility to promote the peaceful use of space and to utilize the new knowledge obtainable from space science and technology for the benefit of all mankind."

I think all of us will heartily subscribe to that statement of principles. It is within that context that the United States Army has provided the launching vehicles which placed the *Explorer* earth satellites in orbit with the primary objective of obtaining useful scientific data about the spatial environment. That data has been made available, without restriction, to the scientific community by elements of the Army Ordnance Missile Command, the U. S. National Academy of Sciences and the International Geophysical Year Committee. We are continuing our cooperative effort to explore space with interested segments of the scientific fraternity.

I want also to use this opportunity to extend my congratulations to the representatives of the Soviet Union for the technological feats they achieved in recent months, beginning with the launching of *Sputnik I* on the 4th of October, 1957, and culminating in the launching of *Sputnik III* on May 15, 1958. We all appreciate the derivative values of competition which can be extremely beneficial in wholly peaceful scientific endeavors such as the launching of satellites for the exploration of the environment of outer space. And I should like to say to our Soviet colleagues that we shall certainly continue to be up there with you, collecting all the data we can in preparation for even more ambitious undertakings which will follow in due course.

My presentation concerns the scientific earth satellites of the *Explorer* series and their launching vehicles, and will be illustrated with a number of slides. In this effort we received major assistance from two sources: the Jet Propulsion Laboratory of California Institute of Technology and the State University of Iowa. The Air Force Cambridge Research Center also participated. So did many other individuals and agencies, including the Vanguard Project of the United States Navy, primarily in tracking and data reduction aspects.

Let me first talk about the carrier rockets for our *Explorer* satellites. We call these carrier rockets *Jupiter-C*, because we have used these rockets in support of the development of a bigger rocket called the *Jupiter*. As Fig. 1 indicates, the *Jupiter-C* rocket consists of a modified *Redstone* rocket serving as first stage and a three-stage cluster of solid propellant rockets placed in a spinning tub which was mounted in the nose of the first stage. The entire *Jupiter-C* thus has four stages.

The standard *Redstone* Missile operates with a thrust of 75,000 pounds and burns alcohol with liquid oxygen as the oxidizing element. For the *Explorer* missions we enlarged the first-stage propellant tanks and selected another fuel, known as hydyne, to replace alcohol. Hydyne is a development of the Rocketdyne Division of North American Aviation Company, our power plant contractor. It yields from 10 to 15 per cent more specific impulse than does alcohol and can be used in an engine designed for alcohol and liquid oxygen without major modification. We actually increased burning time as well as thrust, boosting the latter to 83,000 pounds or 8,000 pounds above the usual *Redstone* thrust.

The total weight of the high-speed clusters in the nose of the *Jupiter-C* is substantially less than the payload weight of the *Redstone* Missile. As a result we could employ longer tanks for the satellite missions and fill these with some extra propellants for the first stage.

The instrument compartment sits atop the tank section and is separated from the latter after first-stage power cutoff. It accommodates the guidance and control equipment for the first-stage flight phase and a spatial attitude control system for horizontal alignment of the separated nose section with the spinning tub when it passes through the apex of its trajectory. The objective is to aim and fire the high-speed clusters prior to apex so that at injection the satellite would be traveling in exactly horizontal direction.

The firing procedure for the *Jupiter-C* was as follows:

The missile takes off vertically under its thrust of 83,000 pounds. During the 155 seconds burning time of the first stage, it is tilted into a trajectory which is approximately 40 degrees inclined to the horizon at cutoff. A few seconds after cutoff, the booster — with that I mean the combined tank and engine section of the first stage — is separated from the instrument compartment. This is done by igniting six explosive bolts which secure the compartment to the front end of the tank section of the first stage. Wrapped around these bolts are six coil springs which have been pre-loaded during the assembly procedure. At the moment the tiny powder charges destroy the bolts, the springs exert a gentle push on the instrument compartment and separate it cleanly from the booster. The velocity increment imparted to the instrument compartment by sudden expansion of the coil springs is in the order of 2.6 fps.

We did not apply a refined cutoff for the first stage of *Explorer I*. Instead we used the so-called depletion technique. This means simply that shortly before the expected burn-out time we energized two contacts. These contacts sensed the pressure in the fuel and the liquid oxygen pump discharge lines. Whichever of these two pressures dropped to zero first triggered a relay which, in turn, closed both propellant main valves controlling the flow into the combustion chamber. In other words, we simply used the instant at which one of the two propellant components depleted to shut the engine down and get a clean cutoff. Cutoff occurred after 157 seconds in *Explorer I*, two seconds later than expected. Simultaneously a timer was triggered which activated the separation mechanism 5 seconds later. This prevented the runup of the booster into the instrument compartment as a result of gradual thrust decay.

In a near-perfect vacuum such as the missile encounters at a cutoff point 58 miles above earth's surface there is no abrupt thrust decay. While the thrust drops quite abruptly to a fraction of its original level, further thrust decay is slow because all the gas in the combustion chamber, plus whatever fuel and liquid oxygen is trapped between the valves and the combustion chamber will expand or after-burn. This will exert a small but noticeable post-cutoff impulse on the booster. Since only the weak spring forces separated the instrument compartment from the booster, we had to ensure that the booster would not collide with the instrument compartment after separation due to this residual thrust. For this reason we allowed the complete missile to coast about 5 seconds and permitted the thrust to decay completely down to zero before actual separation occurred.

From the point of separation, the two portions of the missile coasted through a vacuum trajectory until approximately 404 seconds from take-off. The apex was nearly attained at this time. During the free coasting period, between 157 and 404 seconds, the spatial attitude control system aligned the instrument compartment into an exactly horizontal position with respect to the earth's surface.

This was accomplished as follows:

The same gyroscopes which had controlled the missile up to the cutoff point by means of jet vanes now (after separation) would control a system of compressed air nozzles which were mounted in the tail of the instrument compartment. The reaction thrust of these air nozzles tilted the entire nose section, complete with the spinning cluster of high-speed rockets, into the horizontal direction. The tilt actually occurred substantially faster than the tilt of the trajectory itself. We turned the nose section into the horizontal position relatively fast in order to give the residual errors sufficient time to decay. Thus we obtained the highest possible degree of accuracy in the horizontal alignment by the time apex was finally reached.

Due to our relatively crude cutoff technique, based only on propellant depletion, it was impossible to predict exactly the time at which the apex would be attained prior to takeoff. It was for the same reason impossible to determine exactly and in advance the horizontal distance the missile would have traversed between takeoff point and apex. Because of the curvature of the earth and because the high-speed rocket launcher must be in exactly horizontal position over the local horizon, it was necessary to introduce some auxiliary tracking means to furnish additional data during the flight. Only by catching the moment of apex and by accurate alignment of the spinning tub would it be possible to ignite the high-speed stages in the right direction necessary to obtain orbital flight.

Three independent methods were employed to determine the instant of apex as precisely as possible. First, the missile was tracked by radar. The radar plot was used to predict the instant and point in space at which apex would be reached. Second, we had an accelerometer in the missile which, by means of telemetry, relayed to the ground the velocity build-up of the first stage. Cutoff velocity was then fed into a simple ground computer which predicted the instant of apex transit. Third, standard Doppler tracking network furnished the same information.

The results obtained with these three independent apex prediction methods were introduced into a small calculator which enabled us to evaluate the quality of the three inputs. For example, if one prediction was based upon readings of poor quality, it could be disregarded or its value in determining the average would be reduced to about 20 per cent of the weight of the other methods. We could thus determine a rather reliable average of the apex predictions. The average was then employed to set a timing device which dispatched a radio signal to the missile. It was this signal which fired the second stage. All this had to be accomplished in the four-minute interval between cutoff and apex, of course.

We did not want to fire the second stage exactly at apex but slightly prior to this instant. The second, third and fourth stage had burning times of about 5 seconds each and several seconds elapsed between firing one stage and burnout of the previous stage. Total elapsed time between firing the second stage and fourth stage cutoff was about 24 seconds. Firing of the second stage, therefore, had to occur prior to the predicted apex point. With this lead time the vertical velocity component of the high-speed cluster would be exactly zero at fourth stage cutoff.

The fourth stage appears at the right side of Fig. 1. This is the stage which orbits. It consists of a single 6-inch solid rocket loaded with high energy propellant. The black-and-white striped unit on top of it is the instrumented satellite itself. The entire *Explorer* unit; that is, the empty shell plus the instrumented satellite, weighed 30.8 pounds. The forward portion alone weighed 18.8 pounds and the empty shell weighed 12 pounds. The *Explorer* fourth stage assembly is 80 inches long and 6 inches in diameter. Similar rockets but with

a slightly different propellant were used in the second and third stages. The second stage consisted of a ring of 11 of them. Inserted into this ring was the third stage consisting of three rockets. The single rocket making up the fourth stage sat atop the third stage.

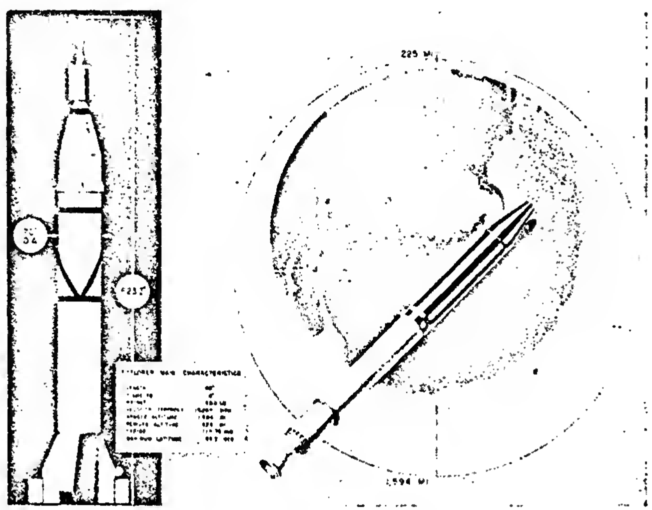


Fig. 1. Jupiter-C (Explorer I). Explorer main characteristics: length 80", diameter 6", weight 30.8 lb., velocity (approx.) 18,000 mph, apogee altitude 1,594 mi., perigee altitude 225 mi., period 114.78 min., maximum latitude 33.3 deg.

Fig. 1 also shows the orbit obtained with *Explorer I*. The perigee altitude of 225 miles and apogee of 1,594 miles corresponds to a period of revolution of 114.78 minutes. From post-launch tracking data, we learned that the angle under which the fourth stage entered orbit was, in respect to the local horizon, as little as 0.81 degrees off, which we thought was a remarkable accuracy in view of the many factors contributing to this error. However *Explorer I* would still have orbited had the error been as high as 4 degrees. Thus a comfortable safety margin was available so far as accuracy requirements for apex attitude alignment were concerned.

The satellite carried two transmitters. The low-powered transmitter in the nose is the same kind as the high-powered one located further aft, but it operates on one-sixth of the power level, radiating only 10 milliwatts instead of 60. It is fed by the same type mercury batteries but since they have about the same capacity in terms of ampere hours as those connected to the high-powered transmitter, they were expected to furnish about six times more lifetime. The high-powered transmitter thus had an expected lifetime of two weeks, while the battery power supply for the low-powered transmitter was expected to last for 2 to 3 months.

The first task of both transmitters was to provide signals for the tracking of the *Explorer*; to prove, that is, that the satellite was in orbit. The high-powered transmitter could be received with any customary VHF receiver but the low-powered one required more sophisticated, narrow band-width receiving equipment.

Specifically, the latter could be received only by the microlock ground stations developed by the Jet Propulsion Laboratory for the Army and by the minitrack network established by the Navy, consisting of a long string of stations stretching from North to South approximately along the 65 longitude west of Greenwich. The stations provide a line across the North and South American continents which must be passed by any object orbiting at any moderate inclination to the equatorial plane. The minitrack network will receive any satellite transmission, provided it employs the right frequency, once per orbit and record the time of passing.

In addition to the task of providing a tracking tool, the transmitters also telemeter to the ground scientific information collected by the satellite. The telemetered data from *Explorer I* consisted of measurements of temperature, micrometeorites, and cosmic rays in space.

Three temperature gauges were carried in the nose and the cylindrical portion of the outer shell to determine outer skin temperatures, and one inside the instrument compartment, behind the high-powered transmitter, to measure the temperature of the heat-insulated instrument package as compared to the outer skin.

For its second test objective *Explorer I* carried several instruments designed to determine the abundancy of micrometeorites in space and to determine how they, or tinier particles commonly referred to as cosmic dust, affect the satellite's surface. Three different instruments were employed. One was a microphone amplifier mounted in the satellite's hull. This would register the impact of a micrometeorite and amplify it. A scale of two circuits was used to switch the frequency of a subcarrier oscillator. Meteorite impact was observed through frequency changes. Dr. BOHN of the Research Institute of Temple University in Philadelphia developed this piece of equipment.

In addition to the microphone there was a micrometeorite erosion gauge, consisting of two instruments in one. A portion of it consisted of 11 wires of extremely brittle metal which were imbedded in an insulating surface. A voltage was applied to the 11 wires in parallel. Each time a micrometeorite struck and broke a wire, the total number of wires connecting the plus and minus busbar would be reduced from 11 to 10, or 10 to 9, or 9 to 8, and so on that the resistance would increase in distinct steps. This change in resistance would be indicated on a sub-carrier oscillator.

Two wires were put out of commission on the first orbit of *Explorer I*. We believe now that they went out during the vehicle's ascent through the atmosphere. Apparently the density of micrometeorites in outer space, at least outside of recurrent meteor swarms is not as high as anticipated. The erosion gauge was prepared by Dr. M. DUBIN of the Air Force Cambridge Research Center.

Final results of the micrometeorite tests will be issued by the Air Force Research Center while Iowa State University will publish the results of cosmic ray measurements.

The third, and most important experiment, was performed by a Geiger counter, compactly packaged and assembled, which was developed by the State University of Iowa under Dr. JAMES VAN ALLEN. The purpose of this counter was to determine the intensity of cosmic primary radiation in outer space.

You will recall that the diameter of the *Explorer* cylinder is only six inches. The total weight of the instrumentation performing all three experiments in *Explorer I* was a mere 10.83 pounds. From this inauspicious springboard there developed a major scientific discovery in physics, which was completely confirmed by the data collected with *Explorer III*.

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The first analysis of the results of Dr. VAN ALLEN's cosmic ray probe proved fascinating and bewildering. *Explorer I*'s radiation counts ran about 30 to 40 per second some 200 to 300 miles above southern California, as had been predicted.

But the count climbed to more than 35,000 per second at the highest altitudes of both *Explorer I* and *Explorer III* when they were over South America and adjoining waters. This figure could possibly have been higher — it was impossible to tell, because the instruments were completely overwhelmed at this extremely high and unexpected cosmic ray count.

Due to existing weight limitations the *Explorer I* counter could report only the number of impinging cosmic primary particles within the counter's sensitivity level. Unable to differentiate between the energy levels, it could not catalog the total into heavier and lighter, or faster and slower cosmic particles.

Moreover, with *Explorer I* we could record impingments only while the transmitter was in direct line of sight with at least one receiving ground station. Since the major portion of the earth is covered with water, or not covered by microlock or minitrack receiver stations, we lost most of the telemetered information over areas where no receiving stations existed.

For more complete data gathering *Explorer III* carried a tape recorder which stored information acquired throughout the entire orbit and reported it, on command, when the satellite passed over a suitably equipped receiving station. This is a small magnetic tape recorder driven by a spring with a little battery-powered electric step motor which wound the spring continuously. A coded radio signal flashed to the satellite from the ground triggered a relay which unlatched the tape reel so that the spring drove the tape through the playback pickup within about 5 seconds. Within this period the transmitter, turned on by the same relay, played back to the ground whatever had been recorded on tape during the last orbit. To conserve power the transmitter was turned off after relaying the tape information. Since the little step relay continued winding the spring, the unit would again play back two hours or so later, after the next orbit. Each time the tape was played back, it was simultaneously cleaned for new information. Consequently the process of recording, storing and playback continued as long as the battery lasted. The system functioned perfectly.

The presence of an exceptionally high particle impingment rate was indirectly concluded from a rather sudden, and complete absence of telemetered pulses while near the apogee of the orbits. The instruments were carried out to altitudes in excess of 1100 kilometers. As it was inconceivable that there existed an area void of any cosmic ray count, this temporary absence of any pulses was interpreted as signifying a blanketing of the Geiger tube by a very dense radiation field. Calibration of the equipment in the laboratory indicated that such complete blanketing of the Geiger tube would require a counting rate of at least 35,000 impacts per second.

It was further concluded that only a small portion of these rays could be of high energy classification, identified as cosmic rays, and that most of the count was made up of a little-known low-energy type, presumably either electrons or protons. There was no way to determine their source, whether the particles came from the sun, or from interstellar space.

The instrumentation in *Explorers IV* and *V* was designed to investigate this exciting radiation phenomenon more closely. To permit the maximum exploitation of our relatively small carrier, the micrometeorite and temperature experiments carried in *Explorers I* and *III* were eliminated. Even the tape recorder in *Explorer III*, that permitted the storage of information gathered throughout orbit for release in toto at a single receiving station, was sacrificed.

Weight reductions in the upper two stages of the *Jupiter-C* launching vehicle, combined with the use of more powerful propellants, permitted an addition of seven pounds of instrumentation in *Explorers IV* and *V* bringing the total satellite instrumentation weight up to 18.26 pounds.

All the instrumentation, devoted to this one experiment, was designed to break down the radiation count into levels of intensity. Four separate radiation counters were carried instead of the single counters in *Explorers I* and *III*. Two Geiger-Mueller tubes, similar to the one each flown in the earlier satellites, were complemented by two scintillation counters. One each of the tubes and scintillators was shielded with lead to eliminate data below certain energy levels.

The shielded counters would respond only to high-energy particles, while the unshielded counters were expected to detect everything. Also, the unshielded scintillation counter had special pickups which could further differentiate between energy levels.

The new instruments in *Explorers IV* and *V* were capable of detecting radiation accurately up to the range of 60,000 particles per square centimeter per second, which is several thousand times greater than the capacity of the equipment used in *Explorers I* and *III*.

The satellite instrumentation for *Explorers IV* and *V* was designed, assembled and tested under the supervision of Mr. JOSEF BOEHM of the Army Ballistic Missile Agency. Dr. VAN ALLEN's institute again furnished the counters and, for telemetry, we used Jet Propulsion Laboratory's proven microlock system.

The highly elliptical orbits planned for *Explorers IV* and *V* were calculated to cover most of the earth's surface. Their orbital inclination with respect to the equator was 50 degrees compared to the 35 degrees of *Explorers I* and *III*. When I was preparing this paper, *Explorer IV* was still sitting on its launching pad, and *Explorer V* was still in the checkout hangar. In the meantime, you will have learned from the newspapers whether or not they have been successful.

This much about our scientific objectives. Other speakers will cover the scientific data obtained from the *Explorers* more fully.

Let me now return to the firing operations proper.

The jet vanes for the *Jupiter-C* caused us some concern for a while. Most of the testing of the rocket engine with the hydyne fuel had been conducted by Rocketdyne at its own California facility while the testing of the jet vanes to determine compatibility was conducted by our Army Agency in Huntsville, Alabama. We were concerned about the combined effect of extended burning time and higher exhaust velocity upon the vanes, since erosion might have reduced our control below the minimum level. It developed that the new fuel eroded the standard jet vanes far less than alcohol.

The extended burning time achieved by using hydyne also required an enlargement of the hydrogen peroxide tank for the engine, simply to keep the turbine running for that extra period. This modification was provided by Rocketdyne.

Fig. 2 shows the instrument compartment of the first stage, which is bolted to the top flange of the booster by six explosive bolts. Numerous cables and tubes connect the instrument compartment and booster. All have quick-disconnect couplings so that at separation the plugs separate and the lines part quickly and easily.

For a research project such as *Explorer I*, with its relatively simple guidance system, access doors were eliminated and the entire cover had to be lifted to service the instrument compartment.

The two dark stripes on the cylindrical part of the instrument compartment are antennas. One is a telemetering antenna; two are part of the Doppler antenna system. On the other side, not visible on this picture, is a radio command antenna. The small protrusions at the bottom house the compressed air nozzles of the spatial attitude control system.

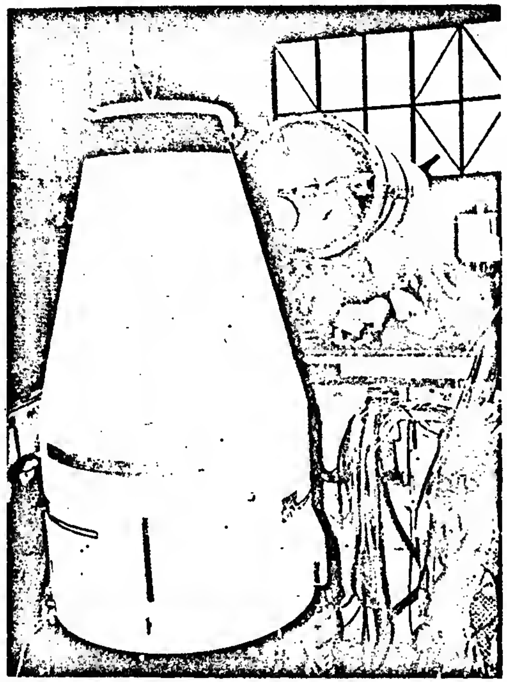

Fig. 2

The test shown in Fig. 2 took place in the Cape Canaveral flight preparation hangar. The instrument compartment was bolted to a rocking table placed at the bottom of a 10-foot pit. The instrument compartment can be rotated and also rocked back and forth in two planes because the table is gimbal-suspended and driven by three electric motors. The gyros are running inside the compartment, thus any error angles developing between the stable gyro reference and the rocking instrument compartment are picked up by potentiometers. Depending on whether the test is concerned with the control phase of the powered first stage flight, or to check the function of the spatial attitude control nozzles operative after separation, a direct response of the jet vanes or the air nozzles occurs. This permits determination, for example, of the correct flow rate in the compressed air nozzles, or points out a sticky control needle, or a wrong polarity. The entire control system in all its functions is thus tested.

Fig. 3 is an exploded view of one of the four compressed air nozzles. The compressed air supply enters the unit through the opening at the bottom. The two nozzles visible here yield a thrust, at full flow, toward right or left of approximately 5 pounds. The air flow is controlled by a small electric motor driving a sprocket wheel. Cogs of the wheel engage the teeth of a push-pull needle shown at the bottom of the picture. As the needle, driven by the motor, moves to right or left, more or less air is admitted to either nozzle. Smooth movements of the needle provide a "proportional control" system in contrast to the "bang-bang" type of control employed in the standard *Redstone* Missile. The refinement was necessary for accuracy reasons. The accuracy observed in rocking tests is one-tenth of a degree.

One of the more difficult problems encountered in the development of *Explorer* was to make this proportional attitude control system absolutely linear under vacuum conditions. With a vacuum outside supersonic flow occurs within the nozzle even at very small rates of air flow. This tended to cause an "s"-shaped response curve which was difficult to straighten out. After some effort, very precise control was obtained, however. Four of the double nozzle units shown in Fig. 3 are attached to the instrument compartment, two for pitch and two for yaw. Roll control was fed to all four electromotors in the form of differential signals.

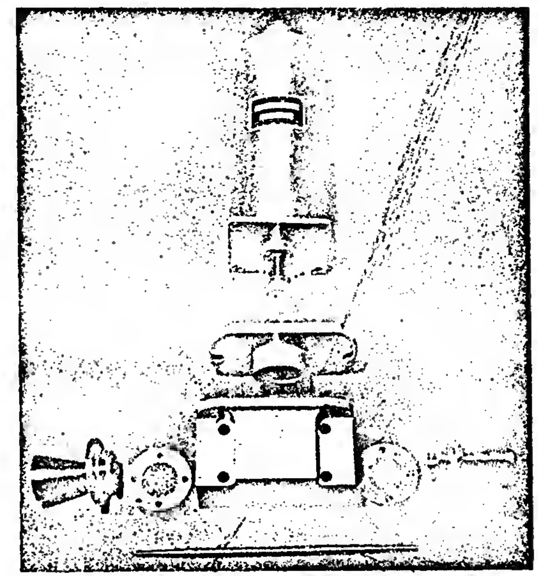

Fig. 3

The instrument compartment and the booster are forced together by hydraulic jacks in order to overcome the compression forces of the springs surrounding the bolts which provide the separation energy.

Fig. 4 shows the spin-up or high-speed stages. Before the launcher can be mounted atop the elongated booster, it must be spin-tested for static and dynamic balancing. A special rig was built which consists of a cage suspended on four rods inside an outer structure. The inner cage surrounds the spin launcher. As the latter is spun up, any unbalances are detected, located and remedied with the aid of a stroboscope.

The white cone at the bottom of Fig. 4 is the non-spinning support of the spin launcher which will later be bolted to the blunt forward end of the first-stage instrumented compartment. Electric motors drive the cluster up to speed; that is, the entire launcher tub with the rocket clusters inside. If the tub is not completely balanced the inner cage will vibrate within the outer frame. The amplitude and pattern of this vibration is measured with a stroboscopic method which permits exact determination of the locations where balance weights must

be added. The technique is widely used in industry to balance dynamically such things as gyroscopes and flywheels. The spin-up facility was designed and developed by the Aerophysics Development Corporation.

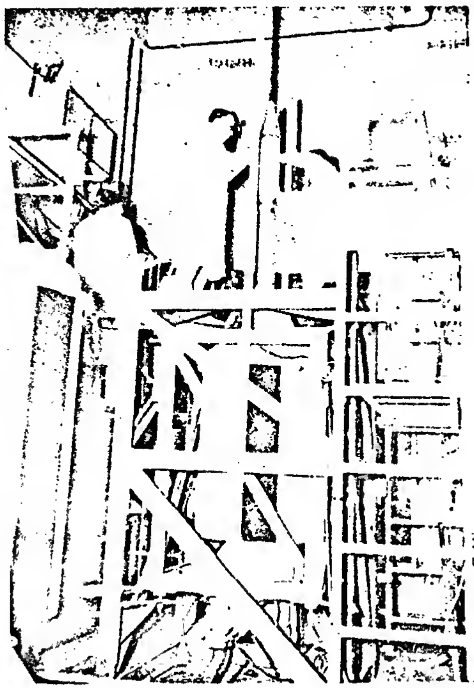

Fig. 4

Rockets for the second and third stages are hidden within the tub while the fourth stage with the satellite payload appears at the top. The tub is an empty aluminum cylinder. Inside are two rows of grooved bosses, one row at the top and the other at the bottom of the tub. The grooves provide support and guidance for lugs attached to the second stage. Inside the second stage are grooves which hold the lugs of the third stage. The lug-and-groove type of holding technique is the exact equivalent of a zero rocket launcher; whenever the second stage has traveled forward as little as half an inch within the tub it is completely free and could make lateral moves of several inches without collision with the tub wall. The same is true of third stage clearance vis-a-vis the second stage.

The fourth stage, however, is mounted atop the third stage in a conical holder attached to the forward end of the third stage. The satellite payload, distinguished by the white longitudinal stripes, is mounted at the top of the fourth stage. Final spin-up and balancing tests were conducted with the live clusters at Cape Canaveral by the Jet Propulsion Laboratory which provided them.

The conical non-rotating support carries the two heavy ballbearings of the spin-up launcher. Underneath it are the two electric motors which spin the tub. The drive mechanism is quite simple. It consists of two sprocket rubber belts which transmit power from the electric motors to the tub.

The procedure for cluster run-up is as follows:

Prior to launching, the tub is rotating at 550 rpm. The missile takes off when this speed has been attained. About 70 seconds after takeoff, a governor controlled by tape programmer inside the missile changes the regulator setting gradually up to 650 rpm. At 115 seconds after takeoff, it rises to 750 rpm. Thus while the first-stage flight is in progress, the rate of spin slowly accelerates.

This procedure was selected to avoid resonance between the spin frequency of the cluster and the bending frequency of the booster. This bending frequency changes as propellants are consumed. The rpm must be kept down to 550 so long as the tanks are full and the bending frequency is correspondingly low. Only after the booster has consumed a substantial volume of propellants can the spin frequency be increased. The increase is about proportional to the increased bending frequency. At no time in flight is a critical frequency experienced.

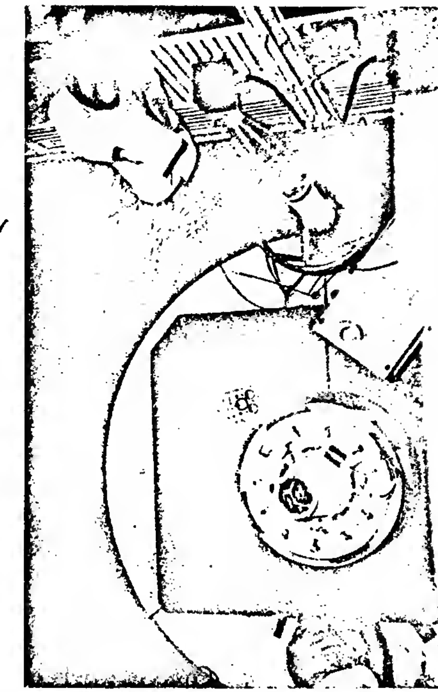

Fig. 5

About 20 seconds before cutoff, the maximum spin rate of 750 rpm has been reached. There is no change in it during the free coasting climb to apex. Because the 750 rpm rate is controlled by a governor, there is sometimes a slightly greater and sometimes a slightly smaller load on the electric motors. These varying loads exert a reaction torque on the instrument compartment attached to the spin launcher and, in free coasting flight, the torque must be compensated by the compressed air nozzles of the spatial attitude control system. Otherwise the instrument compartment could acquire a spin under influence of this reaction with resulting gimbal lock and spilling of the gyroscopes. The thrust of the spatial attitude compressed air nozzles had to be sufficient to cope with these governor reaction torques.

One more consideration in this area should be mentioned. The presence of the spinning cluster in the nose of the instrument compartment means that the attitude control system must tilt a non-rotating body with a heavy gyro mounted in its nose. As it is tilted, the precession forces caused by this gyro must be considered. In practice, the unavoidable precession forces were put to good use; in order to tilt the unit in the pitch direction air was blown out of nozzles pointing in the yaw direction. Thus the precession force of the spinning cluster was employed to tilt it in the pitch direction. The technique and the proper control gain settings had been worked out by analog simulation previously.

Fig. 5 affords a look from a higher platform of the service structure down to the second stage. The front ends of the 11 rockets may be seen emerging from holes in the torus-shaped shroud. It is from there that igniters are placed in the solid rockets. Inside the outer ring forming the second stage are the three rockets of the third stage. On top of them rests the cone which supports the single, fourth-stage rocket.

Fig. 6 discloses the fourth stage, with the satellite payload, being placed into the conical holder on top of the third stage.

In the so-called steam generator the hydrogen peroxide is catalytically decomposed to produce an oxygen-rich steam. This steam drives the turbine which, in turn, drives the two centrifugal propellant pumps which feed the fuel and liquid oxygen into the combustion chamber of the rocket engine.

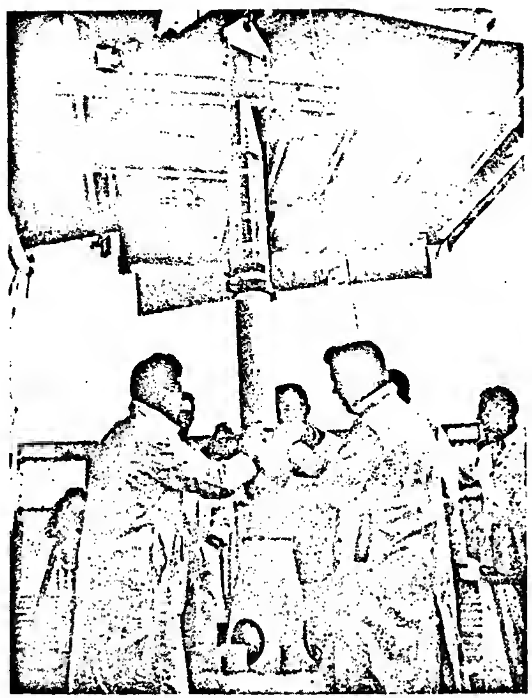

Fig. 6

The launching table is a simple device, made of steel, with four legs through which the rocket jet passes. A conical deflector underneath spreads the jet in horizontal direction. The service structure is mounted on two sets of wheels which run on widegauge rails. The structure is rolled back 300 feet for the launching.

Inside the blockhouse there is a cluster speed control panel. Next comes the rocket engine panel with its ring-shaped safety key. Next down the line is the electrical power supply and network monitoring panel. The next is the panel for the first stage guidance and control system. By observing the instruments the operator can see whether all four rudders are in zero position and whether the gyroscopes are properly leveled. Finally there is a radio equipment panel.

A rack of sequencing recorders is also provided to permit continuous monitoring of such items as hydrogen peroxide temperature, functioning of the instrument compartment cooler, and transmission of the microlock transmitters in the satellite.

The test coordinator calls out the consecutive steps listed in the countdown table, receives compliance reports, and synchronizes the missile preparation with the range operation including tracking stations and photographic groups.

In Fig. 7 the structure has been withdrawn and *Explorer I* awaits launching. Oxygen vapor issues from the lox vent valve, which will be closed prior to tank pressurization which begins immediately before firing. The protruding object at upper right is the preflight instrument compartment cooler. It is a dry ice container, combined with fan and thermostat located inside the instrument compartment. When because of heat dissipation of electrical equipment, the compartment temperature becomes too high, the thermostat cuts in the fan and the fan circulates air through the dry ice until the temperature is reduced enough to stop the fan. Immediately prior to takeoff, the preflight cooler is disconnected magnetically from the missile and falls to the ground. By the time it strikes earth, the missile has left the launcher.

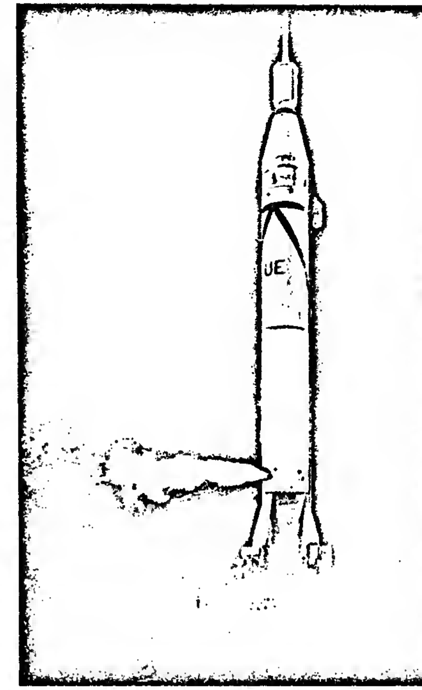

Fig. 7

Simultaneously with disconnection of the preflight cooler, the entire cable connection between missile and ground is severed. Only a few electrical contacts remain in the tail, such as a takeoff contact signal and an emergency cutoff connection in case of inadequate thrust build-up.

The spin-up top is clearly visible. The spin commences at 13 minutes prior to launching.

Fig. 8 shows the antenna system of the microlock receiving station at Canaveral which tracked the initial flight phase of the *Explorers*. More elaborate arrays of such antennae, suitable for interferometric determination of the flight path, were used at additional stations in Africa, Malaya and California. Insulating cylinders made of a plastic form the bases of these antennae. Around them a helix of sheet metal is wound so that it becomes a helical antenna with moderate directional pattern. A wire base provides a reflection shield. Phase comparison between two antennae separated by a given distance indicated the path of the missile-borne transmitter through space.

Typical trailer-mounted microlock stations for the electronic equipment accompany the antennae. In addition to the interferometric stations at Nigeria, Singapore and California there was another, simpler station at Antigua in the Lesser Antilles, 1300 nautical miles downrange from Canaveral. The Navy's

minitrack network provided the North-South picket line previously mentioned which received on the same frequency as microlock, about 108 megacycles per second.

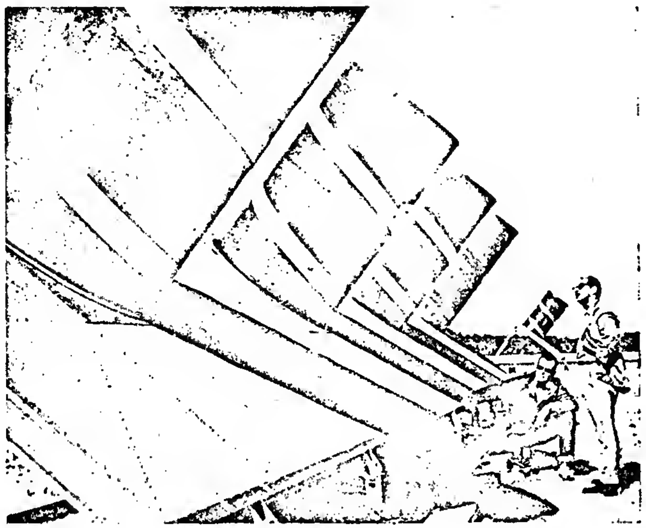

Fig. 8

As long as the first stage was firing, the blockhouse operators could watch recorders of an electronic display system which indicated whether or not the missile was following the predicted path. After first-stage cutoff and separation of the nose section, the next important operation was the prediction of the instant when apex would be reached and the high-speed stages had to be fired. Concurrently with this determination the attitude of the instrument compartment had to be continuously monitored by telemetry to make sure that during the free coasting period the attitude control system did not fail.

Presently the signal had been given for second-stage firing and a few minutes later Antigua reported that both transmitters of *Explorer I* had been clearly heard as the satellite passed that point. The time elapsed between firing the second stage and the passage over Antigua was a pretty good indication of whether the final speed of the fourth stage would be sufficient for orbital velocity. As a result of the measured travel time, it was concluded that *Explorer I* must have settled in a 106-minute orbit. It later on turned out that the actual period of revolution was a little over 114 minutes, and those 8 minutes difference, during which we waited in vain for the signals to be picked up by our receiver station in California, indicating that *Explorer I* had successfully circled the globe, were the longest 8 minutes of my life!

Fig. 9 shows a chart which deals with the time of day at which a firing of the *Explorer* satellite, with orbital data listed in the right upper corner, is permissible from Canaveral from the temperature point of view. Remember that the satellite was covered with dark and white longitudinal stripes to prevent extremes of

heat and cold under the effect of solar radiation or lack of it. The abscissa of the chart indicates month of the year while the ordinate shows the hours of the day.

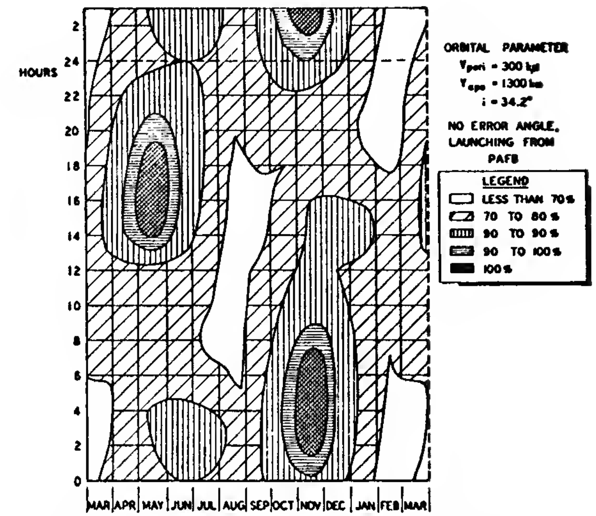

Fig. 9. Time in sunlight for satellite as a function of day and hour of firing. Maximum values during first sixty days of orbiting

To understand the chart, imagine that the orbit were going around the earth in such fashion that the axis of the orbit pointed toward the sun. Then the satellite will always be in sunlight. Now consider the case where the axis of orbit points 90 degrees away from the sun. Then the satellite will spend about one-half of each revolution in sunlight and the other half in earth's shadow. If the orbit is very high, of course, it will be substantially more than 50 per cent in sunlight because the diameter of earth's shadow would be substantially less than orbital diameter. At any angles between zero and 90 degress between axis or orbit and direction toward the sun, different times of exposure to sunlight will be found. But since the earth rotates about its axis and along with the earth's surface goes the firing site, it is clear that these exposure times depend upon the hour of firing. Moreover, as the earth revolves around the sun and therefore the direction toward the sun prescribes a full 360-degree movement throughout the year, exposure times to sunlight must also vary as a function of the time of year.

Fig. 9 indicates that if we launch a satellite during the month of May from Florida between 2 and 7 P.M. in the afternoon (1400 hours to 1900 hours), during the first 60 days of orbiting there would exist a period wherein for a considerable number of consecutive revolutions, the satellite would be in sunlight 100 per cent of the time. Even without additional heat stemming from electrical equipment, the satellite would become too hot. If we launched instead between 6 A.M. and 12 noon, the time of exposure to sunlight will be between 70 and 80 per cent which is acceptable. As long as our satellites do not have devices to actively

control their temperatures, charts like this must be carefully examined to select a favorable launching time.

Fig. 10 shows a series of temperature measurements taken in *Explorer I.* These measurements were taken inside the body, right behind the high-powered transmitter. The abscissa of the chart extends over one complete orbital cycle.

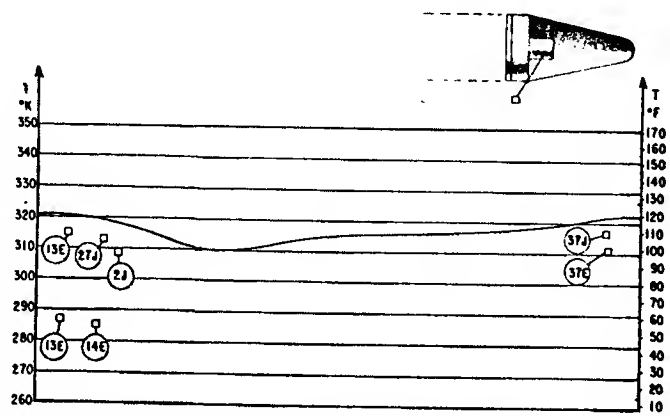

Fig. 10. Instrument temperature (low power transmitter) (Explorer 1). Numbers = No. of revolutions, P = PAFB, J = JPL, E = Earthquake Valley, T = Temple City, S = Singapore, N = Nigeria (Stations)

The bright area indicates that the satellite is in sunlight, the shaded area means it is in the earth's shadow. As you can see, the predicted cyclic temperature changes as indicated by the line are exceedingly small. They vary between 100 and 120 degrees Fahrenheit, about the same temperature region experienced on a hot summer day in the Far West portion of the United States. The fact that the variation is so small is mainly due to the fact that the electronic equipment within the satellite is heat-insulated from the outer skin. The rather densely packed units have a certain amount of heat capacity and simply level off the peaks in variations of outer skin temperatures. The extent to which these peaks can thus be leveled depends solely upon on the ratio between heat capacity of the instrumentation and the heat insulation between the latter and the skin. Note that the actually measured temperatures jibe reasonably well with the prediction, although the data were collected by different observation stations. With a different paint pattern, the entire temperature level could have been shifted by as much as 20 to 30 degrees either up or down.

Explorer I launched on January 31, 1958, is still up in its orbit, but its batteries are dead by now. *Explorer III*, launched on March 26, 1958, completed approximately 1,260 revolutions before its disappearance on June 28, 1958. Its eccentric orbit ranged between a perigee of 116.86 miles and an apogee of 1740.77 miles on the initial pass, and 107.2 miles and 650.2 miles respectively about two weeks before it vanished. The period of revolution dropped from 115.87 minutes initially to 96.885 minutes. The rate of decay measured at apogee was 11.36 miles daily between March 26 and April 11, 11.95 miles between April 11 and 25, 14.99 miles between April 25 and May 31, 15.16 miles from then until June 11 and 16.9 miles thereafter. We are still busy figuring out what this means in

terms of atmospheric densities encountered at these altitudes. At first we had been a bit disappointed about the high eccentricity of *Explorer III*'s orbit, but this eccentricity soon proved to be a bonus as it meant a greater spread between minimum and maximum altitude. For the survey of those newly discovered radiation phenomena which I mentioned previously, this turned out to be extremely valuable.

In summary, we think that with our *Explorer* satellites we have made a valuable contribution to Man's knowledge and scientific comprehension of the airless spaces surrounding the earth. It is my hope that from these humble beginnings the science of astronautics will develop and grow into a broad, permanent, world-wide scientific exploratory program conducted in the same fine spirit that seems to prevail in all programs conducted under the auspices of the International Geophysical Year. The interval between this Congress and the one in Barcelona last Fall has certainly been one of the most significant in the entire history of international science and technology. Cometlike, it has elevated our beloved field of astronautics from ridicule to one of the most important activities men have ever taken up. It has brought mankind closer to the stars, and has made all of us startlingly aware that we must learn to peacefully live and strive together on our own star. For this little planet, which people once were wont to call "the world" *but* which our satellites now circle in 90 minutes, has become too small for war and strife.

SPIN STABILITY OF THE EXPLORER SATELLITE

by
William Bollay, Stanford University

Abstract

The first U. S. satellite, the Explorer was a highly successful satellite in accomplishing its scientific mission. It showed, however, an anomolous and completely unexpected dynamic behavior: It changed its direction of rotation from spinning about its axis of revolution at 10 rpm into a spin about its cross axis at about 2 rpm, after approximately one orbit. According to the classical theory of dynamics of rigid bodies it should have kept spinning stably about its axis of minimum moment of inertia.

This case presents the story of what happened and an explanation of the phenomenon: During the launch and separation four small whip antennas were started vibrating. This vibration absorbed energy which had to come from the kinetic energy of rotation $T = 1/2I\omega^2$. Since the angular momentum $L = I\omega$ of a free satellite is conserved, the energy $T = 1/2I\omega^2 = L^2/2I$ can only decrease if the moment of inertia I is increased. Thus the satellite changed its axis of rotation toward the axis of maximum moment of inertia. For real engineering structures, which always have a certain deflection and internal damping the classical theory of dynamics must therefore be amended to state: A body spinning about its axis of maximum moment of inertia is in stable rotation. A body spinning about its axis of minimum moment of inertia is in stable rotation only in the absence of damping and energy absorption. As a result of this new understanding all spin-stabilized satellites after Explorer were designed to spin about the axis of maximum moment of inertia.

In Part III two other dynamic phenomena encountered in the Explorer development are described:

A. Coupling of Whirl Vibration of the Explorer Cluster with bending vibration of the launch vehicle.
B. Increase of the spin rate by rocket exhaust.

In Part IV some of the historical background is presented on the evolution of the Explorer concept.

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I should like to thank Dr. Willard Wells of JPL and Dr. W. von Braun of NASA Marshall Space Flight Center for their constructive suggestions and for permission to reproduce Part II and Appendix D respectively.

William Bollay

Instructor's Notes

This case is suitable for use in courses in engineering dynamics and mechanical vibrations.

It is suggested that the instructor present the case in separate assignments as follows

First assignment:	Part I (not including the abstract which contains the answer)
and possibly	Part IV (Historical background)
Second assignment:	Part II
Third assignment:	Part IIIA. Particularly suited for a course in mechanical vibrations
Fourth assignment:	Part IIIB. Presents interesting illustrations of the principle of angular momentum

Additional source material on part IIIB is contained in the following reference:

NASA Technical Memo X-75 - Experimental and Analytic Study of Rolling Velocity Amplification during the Thrusting Process for Two 10 inch diameter Spherical Rocket Motors in Free Flight - by C. William Martz and Robert L. Swain

Part IV presents the historical background of the Explorer development. Some potentially important lessons might be drawn from this experience.

The decision makers who proposed the replacement of the proven Redstone booster, by the more elegant but unproven Vanguard were largely a group of scientists rather than engineers. They did not appreciate the value of reliability in well-proven hardware, and the high cost and time required to develop the new Vanguard components.

The fact that the Soviets achieved the first artificial earth satellite has probably had the following unintended beneficial effects upon U. S. policy:

(1) It provided the U. S. with a clear picture of the Soviet ballistic missile capability and their general scientific and technical competence.

(2) It resulted in a greatly improved program in U. S. science education in the high schools and colleges.

This was stimulated by the same scientists who had made the wrong decision in the Vanguard, vs. Explorer argument. They blamed the U. S. delay in coming up with a successful satellite upon poor scientific education in the schools.

(3) It resulted in persuading the U. S. Congress and the American people to provide the necessary funds for a U. S. Space Program. It is an open question whether this could have been done without this spur of Soviet competition.